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The Transient Waveform Control Test Method for
the Qualification of Missile/Rocket Fuze Materiel
to Service Environments

by Abraham Frydman

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U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories

Adelphi, MD 20783

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environments that heretofore could be achieved only during costly field tests. That the method can replicate complex service environments is demonstrated for the launch conditions of the PATRIOT missile fuze. Also presented are test results showing the applicability of the method in the synthesis of classical shock pulses commonly specified in MIL-STD-810C/331A and often invoked in the qualification testing of production missile, rocket, and ammunition fuze materiel.

The report underlines the basic principles and operational features behind the TWC method and presents test execution procedures, as well as testing results for a variety of shaker-synthesized transients. Factors which impose operational constraints on the use of the TWC method are included. Also presented are technical and cost-effective benefits that can potentially be realized from inclusion of the TWC method into the technical data package of missile/rocket fuzes and materiel developed by Harry Diamond Laboratories.

The general nature of the TWC method makes it also applicable to testing of a wide range of Army materiel, subject to the performance limitations of the specific test equipment.

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FOREWORD

For the reader's convenience and for technical clarity, this report has been divided into four distinct chapters, with an appendix included that gives technical specifications.

Chapter I.-- Implementation of the TWC Test Method at Harry Diamond Laboratories

Chapter II.--The TWC Test Method

Chapter III.--TWC Validation Testing--Tabulated Data

Chapter IV.-- TWC Validation Testing--System Configuration and Test Results

Appendix A.--Technical Specifications for the TWC Method

All illustrations have been placed in Chapter IV, where the TWC method is clearly and sequentially developed through photographs, block diagrams, graphs, and computer plots.

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CHAPTER I.--Implementation of the TWC Test Method at Harry Diamond
Laboratories

I-1. INTRODUCTION

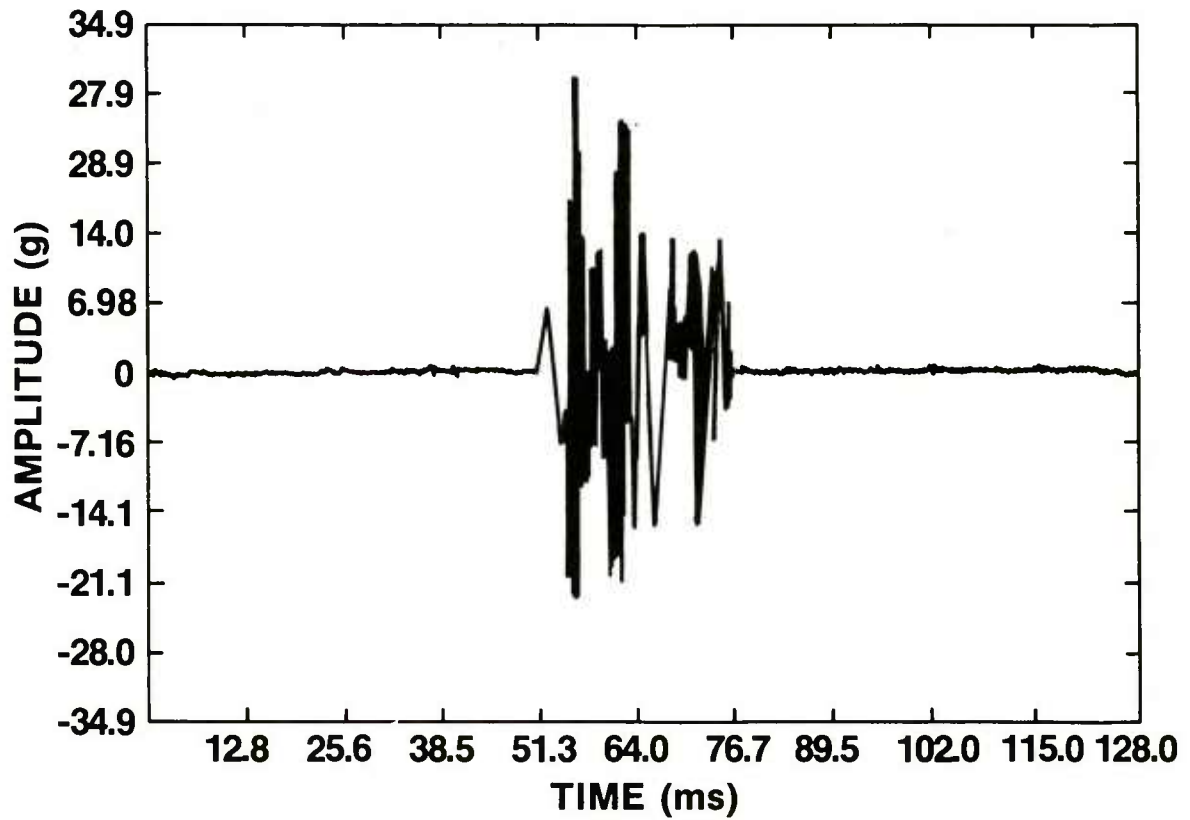
I-1.1 General

The Harry Diamond Laboratories (HDL) tests and validates ammunition and missile fuzes as part of its mission responsibility to bring such products through the design, development, and preproduction stages and into readiness for large-volume production. Performance of this obligation requires that HDL be up to date in all modes of environmental testing to fully support ongoing in-house programs and to assist other agencies and commands in this technology as the need arises. In keeping with this obligation, HDL has extensive and wide-ranging environmental test facilities. This report, however, will discuss only one aspect--the computer-controlled complex vibration/shock testing of ordnance materiel on electrodynamic shakers.

The specific need to test-qualify missile fuzes developed by HDL created an urgent need to increase the precision, fidelity, and efficiency of in-house replication of complex launch and flight vibration/shock environments. Compromises and approximations were being used in testing that were costly, involved complicated test setups, and caused excessive time to be used to run tests and to analyze results. In spite of these shortcomings, such tests were adequate for the evaluation of high-volume, low-cost ammunition fuzes. However, such tests were totally inadequate for validation of high-cost missile fuzes that had to function with near 100-percent reliability. As a result of this serious deficiency, HDL received materials testing technology (MTT) support to obtain hardware augmentation and to have computer software installed on its existing computer-controlled test system for (a) implementing in-house Transient Waveform Control (TWC) testing and (b) establishing test procedures and specifications for the TWC test method to facilitate its incorporation into the qualification process of production missile/rocket fuze materiel. The computerized test equipment (mainframe central processing unit--CPU and peripherals, fig. 1, Ch IV*) and software-based digital servomechanism control techniques were configured so that a variety of complex, service-experienced environments could be synthesized efficiently and reliably on the system's electrodynamic shaker. In addition, test conditions would be arranged so that qualification testing could be accomplished in a time frame consistent with production operation schedules or other HDL testing requirements.

*All illustrations are in Chapter IV, p. 69.

An example of service-oriented dynamic environments which can be replicated using the TWC method is presented below. This transient is too complex to be replicated practically through conventional/mechanical means.



I-1.2 System Description

A simplified block diagram of the TWC system is shown in figure IV-2. Implementation of the digital minicomputers has enabled close coupling of sophisticated control drive techniques to dynamic (real-time) testing. Direct Fast-Fourier Transforms (FFT), Inverse Fast-Fourier Transforms (IFFT), and digital servomechanism control techniques are used to synthesize complex vibration/shock signatures on an electrodynamic vibration shaker. The frequency-dependent transfer function, representing shaker/package dynamics, is first established using trial pulses at 1/8 to 1/4 of full amplitude level. The transfer function value is obtained by normalizing the Fourier Transform of the shaker/package response to that of the specially selected calibration drive pulse. The FFT of the prescribed transient is then computed, and the result is normalized to the transfer function. At this point, an IFFT is computed to convert this function from the frequency domain to time-domain voltage representation. This drive signal, still in digital form, is then converted to analog representation by a digital-to-analog (D/A) converter, smoothed, amplified, and sent forward to excite the shaker. The system CPU (PDP-11/20) employs a 28K-word 16-bit memory.

I-1.3 Synthesized Waveform Verification

During testing, the drive voltage function undergoes repeated iterations through refinements made to the transfer function until the error function, $e_i(t) = x_i(t) - y_i(t)$, representing the component difference between the prescribed amplitude, $x_i(t)$, and synthesized amplitude, $y_i(t)$, results in a specified variance ratio. This variance ratio is a measure of the overall error (E), and is obtained by a normalization of the variance for the discrete error (σ_e^2) to the variance computed for the synthesized transient error (σ_x^2).^{*} The variance in the test amplitude is computed from the standard relationship for the variance, which has been simplified for ease of computation; i.e.,

$$\sigma_x^2 = 1/N \left[\sum_{i=1}^N x_i^2 - N\bar{x}^2 \right] \quad (I-1)$$

where x_i and \bar{x} represent the i^{th} time amplitude and average amplitude, respectively, and $1 \leq i \leq N$.

$$*E = \left(\frac{\sigma_e^2}{\sigma_x^2} \right) 100 \text{ (in percent).}$$

I-1.4 System Operation

All test requirements and abort limits (to safeguard against catastrophic failure) are programmed on a coded test tape. The tape is obtained at the completion of a question-and-answer routine during which the operator is prompted for test information in conversational language by the test system controller. The coded tape provides a permanent record of the prescribed vibration transient and remains available for subsequent use to execute the same test. The program also allows for a time-delayed, repeated execution of the specified transient to automatically comply with the formal three-pulse-per-axis requirements commonly invoked in military test standards (i.e., MIL-STD's 331A and 810C). At the completion of the test, the test system, on command, prints out complete alphanumeric documentation of all test parameters as executed.

I-1.5 Applications and Results

Chapter II, section 1, of this report evaluates in detail the application of the TWC test method; extensive test results are also included. Results are presented for a variety of classical (single-sided) pulses commonly prescribed in MIL-STD-810C or MIL-STD-331A, as well as for complex transients which have been obtained from service environments (i.e., missile launch conditions). Advantages and benefits that can be realized by using the TWC test method for military and production testing applications are presented in sections I-2 (SUMMARY) and I-3 (CONCLUSIONS). Constraining factors which limit the application of the TWC method are presented in section II-1 along with the theoretical concepts which govern the test control process. Section II-2 summarizes the test procedures that are required to execute TWC testing.

Tabulated data are presented in Chapter III, and Chapter IV contains technical specifications of HDL's TWC method, figures IV-1 through IV-28.

I-2. SUMMARY

I-2.1 Test Environments

Use of the computerized TWC method now enables production hardware to be qualified to its own unique service environment, eliminating the risk for potential failure associated with "equivalent" test methods. For instance, the transient shown as an example in the INTRODUCTION was heretofore impractical to achieve in laboratory environments, and the equivalent method selected as an alternative could not always be relied upon to detect potential failure modes. Test

environments that previously were not possible or practical to replicate using other test methods can now be easily replicated in the laboratory or on line. Computer-programmed shock testing takes only minutes; no shock-programmable material, impact computation, or long-duration setup operations are necessary. Moreover, test parameters can be permanently retained on a punched tape or magnetic storage device and can be rerun as many times as desired, thus creating a low-cost, efficient, and highly reliable test procedure. Furthermore, all shock parameters are documented by the computer in the appropriate engineering units and are available immediately after the test. The ultimate goal--automatic synthesis of the product's selective service environment--is a reality.

I-2.2 Test Methods

Test results presented herein are based on the use of the TWC method to effectively replicate a variety of classical (single-sided) pulses, of the type commonly specified in MIL-STD-810C/331A. Such pulses as half-sine and terminal peak sawtooth are replicated as well as special impulsive transient pulses, such as square or exponential decay. Also presented are replication results for complex vibration transients such as those encountered by the fuze of the PATRIOT missile during launch (both axial and radial directions have been considered). Complex vibration signals with amplitudes ranging between ± 40 g and time spans of 20 to 25 ms have been programmed (in closed-loop), resulting in an overall variance error (per eq II-10) between 2.3 and 3.3 percent (see table 1, Ch. III). Shaker (open-loop) synthesis of these transients resulted in a variance error of less than 10 percent (see table 2, Ch. III). For classical pulses, test amplitudes ranging between 10 to 100 g and 3 to 50 ms were successfully programmed with overall variance error between 0.1 to 2.5 percent (see table 1), for which shaker synthesis yielded an overall variance error of less than 10 percent (see table 2). These errors are well within the range that is considered reasonable in practice, and are even lower than the 15-percent amplitude error permissible in MIL-STD-810C/331A. In all cases, shaker performance was limited to 3 kHz.

The relatively low variance error achieved attests to the high degree of quality, accuracy, and replication capabilities of the TWC method. A double-exposure display of the complex PATRIOT/fuze environments during launch, taken at 1/4 and full level while these environments are being synthesized on the vibration shaker (fig. IV-24, Ch. IV), shows no discernable pulse distortions.

I-2.3 Digitization of Original Data

Whereas the programming (definition) of classical pulses or vibration transients which can be represented mathematically is a straightforward procedure, the definition of complex transients which

typically characterize a broad spectrum of service environments for missile/rocket fuze materiel--such as noted herein for the PATRIOT missile fuze (fig. IV-8)--represents a cumbersome and error-prone input problem. Test data bandwidths may require high sampling rates which could yield from several hundred to several thousand data points (depending on the sample rate and pulse duration); therefore, it would be impractical to manually enter such a volume of data as sets of x-y points by terminal.

This deficiency can be overcome in several ways--first, with a separate computer program to digitize the original data (which typically might be available in the form of a graph or a chart); before being digitized the test record must be adequately resolved on the chart to allow for manual tracing of the complete signature. The digitization program, in turn, will curve-fit the data and create data tapes, complete with the pulse description array, in a format recognizable to the TWC program. For the type of data presented here for the PATRIOT fuze, the numeric format (of the input subroutine of the TWC software) must allow at least a three-place accuracy, to avoid singularities in the conversion process (i.e., whereby data points at 9.98 and 10.03 ms both appear as 10.0 ms to the software when the input format does not allow adequate resolution).

By far the more practical input technique is the one which allows the original data, when available on an FM analog tape (i.e., 7 channels, 1/2 in., or 14 channels, 1 in.) to be entered into system memory as the tape is played back through the system's A/D converter(s). In this case, the basic function required of the operator is to specify to the system the appropriate channel sensitivity factor(s) so that the data can be properly calibrated. From this stage onward (and upon operator command) appropriate internal subroutines within the TWC software take over and define the pulse completely. This input procedure will typically require several minutes of operator/machine interaction.

I-2.4 TWC Technical Data Package

Appendix A of this report contains a technical data package (TDP) for the HDL TWC test method. Specifications contained in this TDP are considered universal to the TWC test method and could serve as a guide to HDL fuze contractor(s) in the implementation of on-line, or off-line, TWC testing.

I-3. CONCLUSIONS AND RECOMMENDATIONS

I-3.1 Conclusions

Because of its nature and flexibility, TWC is a practical test control method that can be used to replicate a wide range of missile/rocket fuze service environments. By use of this method, special field environments (e.g., launch transients) for the PATRIOT missile and General Support Rocket System (GSRS) fuzes can be replicated at this facility. HDL also uses TWC to execute MIL-STD-810C/331A-based shock pulses of the type often used to characterize logistical, handling, and tactical environments for missile, rocket, and ammunition fuze materiel. The ability to replicate a specific waveform is subject to the equipment performance limitations and the extent of required pulse conditioning, as described below.

A typical vibration facility having a 7,000 to 18,000 lb-ft shaker/power amplifier subsystem, a 32K-word computer memory capability, and a Digital Control Test System (DCTS) can synthesize accelerations of several hundred g (both positive- and negative-going); pulse periods lasting 2000 to 3000 ms can be achieved subject to performance limitations (velocity change, sample rate, core size, etc).

A TWC facility with capabilities as stated in the paragraph above can be used to replicate a wide range of transient vibration/shock environments suitable for qualification, shakedown, lot acceptance, and other pertinent military testing of missile/rocket/ammunition fuze materiel.

For single-sided (i.e., classical) pulses of the type specified in MIL-STD-810C/33A, it is necessary that the TWC method introduce negative-going pulses before and after the main pulse to satisfy initial conditions of zero velocity and zero displacement of the armature at the end of the pulse. Small or insignificant amounts of waveform conditioning may be required to replicate two-sided waveforms.

Installation of the HDL TWC program on a DCTS whose configuration differs from the HDL system will require program modification; the HDL program software was written for the Digital Equipment Corporation (DEC) PDP 11, model 20 computer.

Additional work is required by the environmental testing community to establish generalized guidelines for TWC control/operations

relating to system calibration, sampling rate, transfer function, evaluation, control error and criteria, spectral resolution, weighting and smoothing techniques, etc.

I-3.2 Recommendations

Use of the TWC test should be included in the technical data packages for the following HDL-developed missile/rocket fuzes: PATRIOT, GSRS, Hawk, and Chaparral.

The TWC test method should be introduced in future fuze programs during the advanced development stage to insure that the production configuration will have been qualified to prescribed service environments.

MIL-STD-810C/331A should be revised for use with the TWC method to include and standardize modified pulse shapes for the currently specified one-sided classical pulses. These revisions should address criteria and recommendations for establishing amplitude reference, pulse shape, permitted variations, and tolerance bands, especially for the conditioned portions of the prescribed pulse.

TWC testing should be incorporated into the TDP's and specifications of other Army fuze materiel which can be mounted on shakers or other controllable platforms. Furthermore, this test method can also benefit product development/qualification testing (e.g., DT-I).

CHAPTER II.--The TWC Test Method

II-1. TWC TECHNIQUE

II-1.1 General Discussion

The computer-based TWC technique offers a realistic and reliable method for laboratory/off-line synthesis of a wide range of vibration/shock service environments. A digital minicomputer (operating from software commands and preprogrammed tapes) assumes complete control of the test and of all test parameters, such as frequency, duration, amplitude, automatic filter equalization, and safe/abort limits, without human intervention. Equalization for the specified control error is achieved automatically. Test amplitude on a bare shaker can be controlled to an average value within 10 percent, and test frequencies can range to 3000 Hz, thereby extending the test capability. More precise amplitude resolution and frequency control can now be achieved due to an increased number of filters (up to 512). Test reliability is further enhanced by the ability to repeat tests by simply feeding in the appropriate preprogrammed, prechecked test tapes.

II-1.2 Equalization Process for the TWC Method

II-1.2.1 System Setup

This section describes the version of the TWC test method as implemented on the HDL/Gilmore Industries TS021 Digital Control Test Systems. Initially, the desired transient waveform, classical or complex in shape, is specified to the controller computer via keyboard commands. The spectral equivalent of this transient waveform is then calculated by an FFT process, which resides in the control system. A standard 12-bit A/D converter (such as the one installed on the HDL system) has a maximum numeric range for the control that is slightly greater than 72 dB, based on ± 2048 counts. Given that all FFT processors have a numeric transfer function, which for this processor is 12, the maximum numeric range available for the spectral definition of the desired transient waveform is $4096/12 = 341.33$, or a 50.7-dB range. The spectral definition is expressed in terms of spectral "want lines," but not all spectral want lines can be used because of range limitations as explained below. Instead, only "major want lines" are used.

II-1.2.2 Equalization Process

The equalization process begins by the test system noise level first being established; this is done by setting the feedback path to expect no more than a 1/8-level pulse and driving a zeroed spectrum with the forward precision drive amplifiers set at the smallest possible gain setting (i.e., 2^{-16}). The spectral equivalent of

four such noise frames is averaged, independent of phase, because the noise magnitude on any line is equally distressing to the phase and magnitude of the transient waveform. This averaged noise spectrum is then doubled and compared with the spectral definition of the prescribed transient waveform. Those spectral lines of the prescribed transient waveform which are considered to be "major want lines" are those lines whose magnitudes are greater than twice the magnitude of the corresponding spectral lines computed from the averaged noise spectrum. The remaining spectral lines (of the prescribed transient waveform) which do not meet these criteria are suppressed to zero value, causing the control to ignore the spectral definition for these lines and consequently produce no drive signal for these lines. The printout entitled "percent of major want lines < 2 * noise level" (p. 33) is a numeric indication of the percentage definition of the desired transient waveform that has been lost to the control as a result of having to suppress the system's noise. Note that without the power amplifier, shaker, and test specimen, the system itself usually exhibits only a fractional percentage loss.

At this point the system is ready to determine the overall transfer function, which consists of its entire electrodynamic frequency response, including test specimen dynamics.

The pulse used to establish the system's transfer function is generated internally by the computer; it is a classical exponential decay pulse with the usual attention given to negative acceleration preceding and succeeding the pulse shape. The pulse duration is selected by the test program to comply with the bandwidth requirements specified for the test; this insures that sufficient response amplitude will be available for the FFT process within the specified test bandwidth. In addition, the negative acceleration regions of the pulse are necessary in order to result in zero terminal velocity and displacement of the vibration shaker at the completion of pulse synthesis. This defined exponential decay pulse is driven iteratively, increasing the drive amplification until the peak of the feedback signal is greater than 91 percent of the expected equalized 1/8-level pulse, regardless of shape deficiencies or distortions (note that no spectral control is exercised during this portion of the equalization). To incorporate this information gathered on the transfer function of the system, power amplifier, shaker, and test specimen, the following two formulas are implemented in acquiring the first drive spectrum, which will result in the first approximation to spectral definition of the desired transient waveform. Using a complex divider in the spectral domain (on a line-by-line basis), a spectral error array is obtained as follows (see fig. IV-3* for explanation of terms):

*All illustrations are in Chapter IV, pp 69-95.

spectral error array =

$$\frac{\text{spectral definition (FFT) of desired transient waveform}}{\text{spectral definition (FFT) of response (feedback) pulse}} \quad ; \text{ i.e.,}$$

$$E_1(w) = F(w)/C_r(w) \quad . \quad (II-1)$$

Then by use of a complex multiply relationship, initial control drive spectrum = spectral definition (FFT) of input (calibration) pulse; i.e.,

$$D_1(w) = C_1(w)XE_1(w) \quad . \quad (II-2)$$

Note that

$$D_1(w) = F(w) \frac{C_1(w)}{C_r(w)} = \frac{F(w)}{H(w)}$$

where $H(w) = C_r(w)/C_1(w)$ is defined as the control system transfer function. Iteratively, at 1/8 level the control method continues in this fashion with the response (from the calibration pulse) replaced by the feedback signal received, based on which a revised transfer function is determined. Successive drive modifications are then implemented by the control method either until the number of 1/8-level pulses specified has been executed, or until the percentage of variance met is within the specified alarm limits (the second criterion is controlling).

Note that the spectral error array is allowed by the servocompressor to apply greater correction per control update to the lower frequency region of the spectral lines as compared to the higher frequency region. Additionally, the drive amplifier is ranged to keep the drive spectrum by use of the maximum numeric range possible for each spectrum driven through the IFFT process using the iterative relationships at 1/8 level; equation (II-2) can now be stated as

$$\begin{aligned} (\text{spectral drive array})_i &= (\text{spectral drive array})_{i-1} \times \\ &(\text{spectral error array})_{i-1} \quad , \end{aligned} \quad (II-3)$$

where the spectral error array is adjusted continuously based on feedback information. Proceeding next to the 1/4 level, the above equations are used and the iteration continues either until the specified number of pulses has been executed or the percent variance has been controlled to within the alarm limits (the second criterion is

controlling; i.e., the 1/4-level pulse will not be synthesized if the alarm limits are exceeded). Exceeding these limits implies that the controller cannot equalize the prescribed pulse. If the abort/alarm limits are not exceeded, the system will be commanded by the operator to execute 1/2-level and full-level amplitude pulses using the same control and iteration methodology described above. Obviously, the iterative equalization process starts at low levels (1/8 to 1/4 range) in order to protect the test package as well as to accurately determine a refined value for the transfer function. The latter is of particular importance because experimental observations indicate that the transfer function does not increase linearly with a linear increase in the level of excitation, in spite of theoretical predictions to that effect.

II-1.3 Error Analysis

Deviations between the prescribed and shaker-synthesized transients often occur in practice due to constraints imposed by the control algorithm or as the result of performance limitations inherent in the test equipment. For example, a lower than required sample rate will yield an inadequate FFT spectral definition; a peak-notch control in excess of 60 dB may cause distortion of the drive signal. It is of interest to determine the extent of these discrepancies over the entire time-region of the transient, in order to establish a statistical or weighted error (deviation) criterion against which the transfer function can be iterated, so as to improve its definition. Unlike MIL-STD-810C or -331A, which specify the allowable error (deviation) for classical pulses (i.e., typically ± 15 percent on amplitude and as much as 30 percent on duration), no such standard allowance exists for complex or nonclassical transient waveforms. The following definition of pulse error offers a means or a technique by which such error can be quantified, and could also be used to measure the quality and accuracy of the test control algorithm.

Let e_i = the i^{th} positive or negative error component (deviation or difference) between the amplitudes of the prescribed (x_i) and the synthesized (y_i) transients, as shown in figure 4; i.e.,

$$e_i = x_i - y_i \quad . \quad (\text{II-4})$$

Note that e_i , x_i , and y_i are all functions of time, and that $i = 1, 2, 3, \dots, N$ is an index of described data points in the time domain.

Let the mean level of the specified transient in the time domain be equal to \bar{x} , where

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad (\text{II-5})$$

and the mean error computed from a similar relationship,

$$\bar{e} = \frac{1}{N} \sum_{i=1}^N e_i \quad (\text{II-6})$$

The variance for the discrete data points (located on the transient waveform) with respect to the mean value of the transient is computed from the standard relationship for the variance (i.e., σ_x^2),

$$\sigma_x^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2 \quad (\text{II-7})$$

And the corresponding variance for the discrete errors with respect to the mean value of the error is given by a similar expression for the variance:

$$\sigma_e^2 = \frac{1}{N} \sum_{i=1}^N (e_i - \bar{e})^2 \quad (\text{II-8})$$

The overall variance in the time domain, E, can now be expressed in units of percent, in terms of the above expressions; i.e.,

$$E = \frac{(\sigma_e)^2}{(\sigma_x^2)} \times 100 \quad (\text{II-9})$$

For ease of computation, the expression for the variance of the standard can be rearranged and simplified as follows:

$$(x_i - \bar{x})^2 = x_i^2 - 2 x_i \bar{x} + \bar{x}^2 \quad (\text{II-10})$$

Thus,

$$\sigma_x^2 = \frac{1}{N} \left[\sum_{i=1}^N x_i^2 - 2 \bar{x} \sum_{i=1}^N x_i + \sum_{i=1}^N \bar{x}^2 \right] \quad (\text{II-11})$$

Since

$$\sum_{i=1}^N \bar{x}^2 = \bar{x}^2 \sum_{i=1}^N (1) = N\bar{x}^2$$

and

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \text{ or } \sum_{i=1}^N x_i = N\bar{x} \quad , \quad (\text{II-12})$$

substituting in equation (II-12), we have

$$\sigma_x^2 = \frac{1}{N} \left[\sum_{i=1}^N x_i^2 - 2N\bar{x}^2 + N\bar{x}^2 \right] \quad , \quad (\text{II-13})$$

and

$$\sigma_x^2 = \frac{1}{N} \left[\sum_{i=1}^N x_i^2 - N\bar{x}^2 \right] \quad . \quad (\text{II-14})$$

Note that this is more rapidly calculated than the original equation, since \bar{x} has already been found and, considering the fewer steps in this final equation, numeric error problems can be greatly reduced.

As noted from the test results for closed-loop operations (Ch. II-3.4), the variance error (eq II-9) ranged between approximately 0.1 and < 5.0 percent.

II-1.4 Limiting Factors--Pulse Synthesis and Description

II-1.4.1 Pulse Modification/Execution

Use of the TWC method to replicate classical or complex shock pulses on a vibration shaker is subject to the physical constraints of the process. Namely, the initial and terminal magnitude of acceleration, velocity, and displacement of the shaker must equal zero. Furthermore, the maximum magnitude for each of these parameters is subject to design limitations associated with the specific shaker/power-amplifier system. At HDL these limits are ± 0.5 -in. double-amplitude displacement, ± 70 -in./s velocity limit, and ± 120 -g peak acceleration. To bring the shaker to terminal displacement, velocity, or acceleration, the synthesized shock pulse--when integrated in the time domain--must yield zero area under the specific time-history curve; i.e., the pulse must contain negative area regions which will cancel out the positive regions of the pulse. For a complex pulse which contains both positive and negative acceleration components (such as shown for the PATRIOT fuze--see Ch. II-3), quite often the overall integral is almost equal to zero, and little or no modification to the original data

may be required to result in total area cancellation. On the other hand, classical pulses are one-sided and, therefore, may require modifications in the form of negative acceleration regions that must be inserted before and after the pulse to bring about total area cancellation. This is shown schematically in figure IV-5, for several classical pulses. Since the negative regions of the pulse are not part of the prescribed transient, it is desired to keep the amplitude in the negative region to a minimum--usually not in excess of 10 percent of pulse peak. To achieve this, the bulk portion of the data frame (as much as 80 percent) may have to be allocated to the distribution of the negative regions, leaving only about 20 percent as a useful region for pulse synthesis.

For example, the magnitudes of the terminal velocity and displacement of an unmodified half-sine pulse are given by the following expressions:

$$\dot{x}(t=t_0) = 2t_0 \ddot{x}_0/\pi \neq 0 \quad (\text{II-15})$$

$$x(t=t_0) = t_0^2 \ddot{x}_0/\pi^2 \neq 0 \quad (\text{II-16})$$

The magnitude of negative acceleration ($\alpha \ddot{x}_0$) can be determined from the constraint for the modified pulse that the velocity of the shaker at the end of the excitation process be equal to zero as shown in figure IV-5; i.e.,

$$|2Aa_1| = Aa_2 \quad (\text{II-17})$$

The modified portion of the pulse is a trapezoid whose area is computed as follows:

$$Aa_1 = \frac{(t_1 + \beta t_1)}{2} \alpha \ddot{x}_0 = \alpha \frac{\ddot{x}_0 t_1}{2} (1 + \beta) \quad (\text{II-18})$$

The specified portion of the pulse (Aa_2) is a sinusoid whose area is computed by the integral below:

$$\begin{aligned} Aa_2 &= \int_{t_1}^{t_1+t_0} \ddot{x}_0 \sin\left(\frac{\pi}{t_0}\right) (t - t_1) dt \\ &= -\frac{t_0 \ddot{x}_0}{\pi} \cos\left(\frac{\pi}{t_0}\right) (t - t_1) \Big|_{t_1}^{t_1+t_0} \end{aligned} \quad (\text{II-19})$$

$$\begin{aligned}
&= \frac{-t_0 \ddot{x}_0}{\pi} \left\{ \left[\cos \left(\frac{\pi}{t_0} \right) (t_1 + t_0 - t_1) \right] - \cos \left(\frac{\pi}{t_0} \right) (t_1 - t_1) \right\} \\
&= \frac{-t_0 \ddot{x}_0}{\pi} [\cos(\pi) - \cos(0)] = \frac{2t_0 \ddot{x}_0}{\pi} \\
Aa_2 &= \frac{2t_0 \ddot{x}_0}{\pi} \tag{II-20}
\end{aligned}$$

Substituting equations (II-18) and (II-20) into equation (II-17) yields

$$|\alpha \ddot{x}_0 t_1 (1 + \beta)| = \frac{2t_0 \ddot{x}_0}{\pi} \tag{II-21}$$

By setting $(t_0/t_1) = \gamma$, where $0 < \gamma < 1$, an expression for α can be obtained in terms of the principal pulse regions

$$\alpha = \frac{2\gamma}{\pi(1 + \beta)} \tag{II-22}$$

and

$$\gamma = \frac{\alpha\pi(1 + \beta)}{2} \tag{II-23}$$

Since the total duration of the data frame is equal to $(2t_1 + t_0)$, the time period which must be reserved for waveform synthesis can be determined as follows:

$$T_{tot} = 2t_1 + t_0 \tag{II-24}$$

using the relationship for γ above,

$$t_0 = \left(\frac{\gamma}{2 + \gamma} \right) T_{tot} \tag{II-25}$$

*where t_0 is the available time for the specified pulse within the total time frame (T_{tot}) required to equalize the pulse.

for $\alpha = 10$ percent and $\beta = 50$ percent, $\gamma = 0.236$ from equation (II-22), and $t_0 \approx 10.5$ percent T_{tot} from equation (II-25).

Thus, only about 10 percent of the time frame will be available for waveform synthesis (i.e., the remaining 90 percent will be used to stretch the negative regions of acceleration so as not to exceed an α of 10 percent). The HDL TWC software permits the operator to manually override the default value of 10 percent set for α in the control program, whereas β is fixed at 50 percent. By increasing the value of γ , a longer portion of the data frame (20 to 40 percent) can be utilized for pulse synthesis, but this is done at the expense of a corresponding increase in the magnitude of negative acceleration, an increase which may not be permissible from the standpoint of test specifications (e.g., exceeding 10 percent of the peak acceleration of the specified pulse).

The useful portion of the data frame which is available for waveform synthesis, as determined by the HDL TWC software, is governed by the following relationship; note that quantity α is computed from this relationship and from equation (II-22).

$$\Delta t = \eta \left(\frac{NS}{SR} \right) , \quad (\text{II-27})$$

where $\Delta t = \tau_0$ = the time duration for the prescribed transient (in seconds), NS = number of samples in the time domain = $3 \times \text{No. of spectral lines specified for the frequency domain} \equiv 3(NL)$, and SR = sample rate (samples/s) $\equiv 3f_{\text{max}}$.

f_{max} = bandwidth of data expressed in units of Hz = upper limit of test frequency, also known as the Nyquist cutoff frequency.

η = percentage of data frame available for synthesis of the prescribed pulse, $\eta = t_0/2t_1 + t_0$. For the default option, $\eta = 0.20$.

Example: For a data bandwidth of 5000 Hz and 512 FFT spectral line definition, the useful portion of the pulse is given as

$$\Delta t = (0.2) \frac{3 \times 512 \text{ samples}}{3 \times 5000 \text{ samples/s}} = 20.48 \text{ ms} .$$

*N real-valued data points in the time domain will yield $N/2$ complex-valued spectral lines in the frequency domain. Thus, a 1024-point FFT will yield 512 spectral lines from 0 frequency to f_{max} .

The sampling rate per point is given as

$$\Delta t/\text{point} = \frac{1}{3 \times 5000} = 67 \mu\text{s} \quad .$$

Given the following limitations for the HDL TWC software and test system (Gilmore Industries, model T5021),

$$(a) \quad 64 \text{ lines} < NL \leq 512 \text{ lines},$$

$$(b) \quad 500 \text{ Hz} \leq f_{\text{max}} \leq 5000 \text{ Hz}.$$

The standard range available for pulse synthesis is computed as follows:

$$(\Delta t)_{\text{max}} = 0.2 \frac{3(NL)}{3(SR)} = 0.2 \frac{NL}{BW} = 0.2 \frac{512}{500} = 204.8 \text{ ms} \quad .$$

And $(\Delta t)_{\text{min}} = 0.2 \left(\frac{64}{5000} \right) = 2.56 \text{ ms}$; hence, $2.6 \text{ ms} < \Delta t < 205 \text{ ms}$. Note, for example, that of the total of $(3)(64) = 192$ samples taken at the sample rate of $(3)(5000) = 15,000 \text{ Hz}$, only about $(3)(64)(0.2) = 38$ samples will be available for pulse definition. Since this may be an unacceptably low figure for some applications, the sampling rate will have to be reduced so that more data points can be read in for definition purposes. Alternatively, the system's core memory, currently at 24K-words, will have to be expanded (i.e., to 28K-words) to allow for larger data intake. However, expansion beyond the 28K-word range is not feasible since extensive data management routines are required that are not currently available for the HDL test system.*

II-1.4.2 Limitations on Complex Pulse Description

Theoretically, if we use a 512-line FFT of radix 3 for spectral definition and the 20 percent of the frame for pulse description as a general rule, 307 points of the total of 1536 time points (3×512) throughout the frame should be available for pulse description. In practice, however, this is not the case, for several

*The D706 system interface device (fig. IV-1 and -2) uses some memory addresses between 28 and 32K-words. Therefore, to expand to 32K-words would require several wiring changes on the D706 and reassembly of all operating system programs to access the new hardware addresses. Even with this change only 30K-words are available, because the last 2K-words are dedicated to Digital Equipment Corporation hardware accesses, whether that hardware exists or not.

reasons. For an extremely complex pulse, with sharply defined "peaks" and "valleys" of acceleration (as a result of "ringing" or high numerical data slopes), any digital control scheme will require at least several points to define the pulse shape between each peak and valley, thus enabling proper synthesis. This would reduce the utilization of the 307 available points, depending on the number and nature of such peaks and valleys, by approximately 8 to 10 points per amplitude used to represent specific peaks or valleys (a small reduction at worst). The loss of effectiveness of the full range of data points depends on the manner in which the points of description are specified, and on the internal (digital) representation utilized in the control program. The points are specified in fractions of a millisecond and are internally represented by a 16-bit floating point number. Since 8 bits are used to specify the mantissa the accuracy of this number is no greater than $1/256$, regardless of its range (which easily covers from 0.066 to 100 ms). Therefore, if the bandwidth is 5000 Hz, the resulting sampling rate will be 67 μ s per point.

Defining data points by specific time entries with the above accuracy leads to difficulties as the following example shows: Consider 19.98 ms as a point defining the acceleration time level of a transient; the next specified time point is 20.03 ms. All other acceleration time points entered in between these data points will be truncated to 19.90 ms. Obviously, this accounts for some error, as discussed above, but there also exists a problem in the ASCII-to-log or floating-point conversion within the math-pack* such that internal representation is sufficiently accurate but numeric input will not represent this accuracy. This is a deficiency in the conversion routine, which will handle only 2-1/2 decimal place accuracy; therefore, 19.98 ms appears internally as 19.9 ms and 20.03 ms as 20.0 ms. This spread of 100 μ s is greater than the 67- μ s sampling rate (5000 Hz) and is the cause of the problem at high sampling rates. This implies that for the present conversion capabilities of the HDL TWC software, data points can be read (through X-Y entries on a teletypewriter or terminal) no closer than 100 μ s apart. This corresponds to a sampling rate of 10,000 Hz and data content of 3300 Hz, since the sampling rate is performed at three times the bandwidth (well above the Nyquist rate of twice the bandwidth). Consequently, for sampling rates requiring point spacing closer than 100 μ s, the software package (math-pack) will have to be modified to eliminate the conversion constraints. The present constraining factor (within the math-pack) is considered to be the limitation imposed by the F8.8 numeric format, which leads to conversion

*The math-pack is the portion of the control software dedicated to the numerical representation of the specified transient, scaling of the data, and to successive interpolation between entry points.

error instead of what appears to be a representation error. Such modification will allow a more efficient utilization of the total number of points available for pulse representation (i.e., approximately 300 points for X-Y entries on the data tape for the spectral conditions specified above).

II-2. TESTING PROCEDURES

This section contains descriptive information and test procedures for the TWC software that has been installed on the HDL/Gilmore Industries T5021 test system.* The test procedures outline a sequence by which the operator, using conversational English, can (1) initiate the system, (2) specify through keyboard commands the test requirements and parameters to be executed, (3) create and punch a permanent record in the form of the test data (paper) tape, (4) execute the prescribed test, and (5) display and list the synthesized and specified transient(s) as produced on the vibration shaker, including the corresponding error function, Fourier spectrum, and drive signal.

The software loading procedure, from system initiation to the test execution phase, is shown in figure IV-6. The application of the above procedures to synthesize a decaying sinusoid is presented as an example. The synthesized transient and resulting error curve are presented in figures IV-7(a) and (b). Information presented in this section has been extracted from the HDL operator manual for TWC testing; the manual was generated by Gilmore Industries under contract to HDL.* This manual essentially translates the entire TWC test process, written in proprietary machine language, to conversational English to allow for efficient interaction between the operator and the test control software. The typical operator is not proficient enough in machine language to be able to program a test system using machine language instructions and complicated editing routines.

Excerpts from this manual follow.

*The test control software for the HDL TWC method was developed under HDL contracts DAAG-39-76-C-2004 and DAAG-39-77-M-2554.

OPERATING COMMANDS

ALL COMMANDS CONSIST OF A 2 LETTER COMMAND CODE.
SOME COMMANDS ARE FOLLOWED BY PARAMETERS GIVING FURTHER
INFORMATION NECESSARY FOR THE COMMAND.

PARAMETERS CAN CONSIST OF ONE OR TWO LETTERS
OR A VALUE (INTEGER OR NUMBER + FRACTION).

THE PARAMETERS ALLOWED FOR A PARTICULAR COMMAND
WILL BE SHOWN ENCLOSED IN CORNER BRACKETS: '<' & '>'
WITH THE SPECIFIC PARAMETERS SEPARATED BY COMMAS
WITHIN THE CORNER BRACKETS.

COMMAND CODE LIST

TWO SETS OF PARAMETERS MODIFY THE OUTPUT COMMANDS
IN GENERAL:

A) <WA,GO,IN,ER> ARE PARAMETERS SELECTING WHICH
SPECTRUM GENERATED BY SHOCK TIME HISTORY IS TO
BE OUTPUT ON A PARTICULAR PERIPHERAL

WA SELECTS THE WANT (DESIRED) TRANSIENT DESCRIPTION
GO SELECTS THE GOT (RETURN PATH) TRANSIENT DESCRIPTION
IN SELECTS THE DRIVE (FORWARD PATH) TRANSIENT DESCRIPTION
ER SELECTS THE (WANT - GOT) CALCULATION RESULT

B) <CO,RE,IN,PO,MA,PH,TI> ARE PARAMETERS SELECTING
THE FORMAT IN WHICH THE SPECIFIED SPECTRUM
IS TO BE OUTPUT.

CO(COMPLEX) OUTPUTS THE COMPLEX PAIRS OF A SPECTRUM.
FOR THE PRINT COMMAND, AND ONLY THE REAL PORTION
OF THE SPECTRUM FOR OTHER VALID COMMANDS.

RE-REAL) OUTPUTS THE REAL TERMS OF A SPECTRUM.
FOR DISPLAY/PLOT COMMANDS, ONLY THE ABSOLUTE VALUE
OF THE TERM IS GIVEN

IM(IMAGINARY) OUTPUTS THE IMAGINARY TERMS OF A
SPECTRUM. FOR DISPLAY/PLOT COMMANDS, ONLY THE
ABSOLUTE VALUE OF THE TERM IS GIVEN.

PO(POLAR) OUTPUTS THE SPECTRUM IN POLAR
FORMAT(MAGNITUDES AND PHASE ANGLES). FOR PLOT/DISPLAY
COMMANDS, ONLY THE MAGNITUDES ARE GIVEN.

MA(MAGNITUDES) OUTPUTS ONLY THE MAGNITUDE PORTION
OF A POLAR SPECTRA

PH(PHASE) OUTPUTS ONLY THE PHASE ANGLE PORTION
OF A POLAR SPECTRA

TI(TIME HISTORY) OUTPUTS THE TIME HISTORY GENERATING
THE SPECTRA

OUTPUT COMMANDS:

PO <WA,GO,IN> PUNCHES A PAPER TAPE OF THE SELECTED
SPECTRUM IN COMPLEX FORMAT ONLY.

PR <WA,GO,IN> <CO,RE,IM,PO,MA> PRINTS THE SELECTED
SPECTRUM IN THE SPECIFIED FORMAT.

EXAMPLES:

PR WA PO

PR GO RE

PR IN PH

PL <WA,GO,IN> <CO,RE,IM,PO,MA,TI> PLOTS THE SPECTRUM
IN THE FORMAT SELECTED BY THE 2ND PARAMETER.

CO & RE BOTH DISPLAY THE REAL TERMS.(ABS. VALUE)

IM DISPLAYS THE IMAGINARY TERMS

PO & MA BOTH DISPLAY THE MAGNITUDE PORTION

PH DISPLAYS PHASE ANGLES IN BAR-MODE

TI DISPLAYS THE TIME HISTORY OF THE SPECTRUM

PL AB ABORTS ANY PLOT AND ALSO ABORTS THE DISPLAY

PL MO <LI,BA> SETS THE PLOT MODE. LI IS LINE MODE
(STANDARD) BA IS BAR MODE, USED NORMALLY FOR PHASE ANGLES.

PL SP XX SETS THE PLOT SPEED BY USING THE VALUE XX
 AS A DELAY LOOP COUNT. THUS, LARGER VALUES OF XX
 PRODUCE A SLOWER PLOT SPEED
 PC <TI,CO,PH> PRODUCES A QUESTION - VALUE -
 THE ANSWER TO WHICH WILL PRODUCE A HORIZONTAL LINE
 AT THAT LEVEL ON THE PLOTTER
 ZE AND FS CAUSE THE PLOTTER TO MOVE TO THE
 LOWEST AND HIGHEST VALUES THAT CAN BE OUTPUT, RESPECTIVELY
 VALUES ARE PRINTED ADDITIONALLY ON THE TTY
 DC TERM CONTROL FOR DRIVING ANY SHAKER MUST BE POSITIVE
 INDICATING <DP> COMMAND. <DN> IS USED ONLY FOR NON-SHAKER
 APPLICATIONS.
 <HE>, HELP COMMAND LISTS THE SYSTEM'S AVAILABLE 2-LETTER COMMANDS

LOAD FFT? Y/N:

CC

M B MONITOR V005B OF 6-7-73

SHOCK TIME HISTORY IN RESIDENCE
 VL009ES JULY 1976

RU

HDL SHOCK TIME HISTORY
 VL009ES

> LI

1 SIGNAL LOSS % GAIN	25
2 XDUCER SENSITIVITY	54.1
3 G'S PEAK FULL LEVEL	5
4 LOW EQ. LEVEL(1/N) N	12
5 # LOW LEVEL PULSES	5
6 # 1/2 LEVEL PULSES	25
7 # FULL LEVEL PULSES	40
8 MAX 1/4 LEVEL PULSES	40
9 MIN 1/4 LEVEL PULSES	5
10 % VARIANCE ALARM	10
11 % VARIANCE ABORT	15
12 LOW ALARM LIMIT	2
13 LOW ABORT LIMIT	5
14 HIGH ALARM LIMIT	1
15 HIGH ABORT LIMIT	5
16 TIME BETWEEN PULSES	10
17 # SPECTRAL LINES	512
18 BANDWIDTH (HZ)	2000
19 PULSE DURATION (MS)	45

OF DEFINABLE TIME PTS. MAX. = 270
 DELTA TIME MIN. (MS) = .167

20 ERROR# 0

```

> ED
0 EDIT LINE #          0      =5
5 # LOW LEVEL PULSES    5      =10
# 1/2 LEVEL PULSES      25     =
7 # FULL LEVEL PULSES   40     =
8 MAX 1/4 LEVEL PULSES  40     =
9 MIN 1/4 LEVEL PULSES   5      =7
10 % VARIANCE ALARM     10     =

```

```

> DE
PULSE DURATION (MS) : 45

```

```

PULSE CODE: SP
# OF DEFINABLE TIME PTS. MAX. = 270
DELTA TIME MIN. (MS) = .167

```

```

DATA TAPE INPUT? Y/N : N

```

```

# OF POINTS      70      = 67

```

```

POINT #      = 1

```

```

POINT #1
TIME (MS)      .75      = 1.25
G/S            0         = 1.0352

```

```

POINT #2
TIME (MS)      1.5      = 2.5
G/S            0         = 2.0

```

```

POINT #3
TIME (MS)      2.25     = 3.75
G/S            0         = 2.8284

```

```

POINT #4
TIME (MS)      3         = 5.0
G/S            0         = 3.4641

```

```

POINT #5
TIME (MS)      0         = 6.25
G/S            0         = 3.8637

```

```

POINT #6
TIME (MS)      0         = 7.5
G/S            0         = 4.0

```

```

POINT #7
TIME (MS)      0         = 8.75
G/S            0         = 3.8637

```

Continue procedure until pulse is fully specified.

> PU WA
CHECK HSP. TYPE RETURN.

ENTER TEXT. ALT-MODE TO STOP.
DECAYING SINE WAVE EXAMPLE 45 MS, 2000 HZ, 512 LINES,
FOR HDL MANUAL. 8/2/76 KNW

PR PD
?
> PR WA PD

POLAR SPECTRA
OF LINES = 512
BANDWIDTH (HZ) = 2000
DELTA BANDWIDTH (HZ) = 3.91

XDUCER SENS. = 54.1

N	:	MAG(N)	ANG(N)	MAG(N+1)	ANG(N+1)
1	:	8.28 E-02	138	.106	296
3	:	.107	86.3	9.33 E-02	250
5	:	7.42 E-02	33.3	6.76 E-02	161
7	:	.100	302	.131	101
9	:	.14	264	.120	63.5
11	:	9.74 E-02	199	.140	326
13	:	.236	121	.342	288
15	:	.431	99.7	.484	273
17	:	.494	87.2	.461	261
19	:	.39	74.7	.296	247
21	:	.195	54.2	.110	210
23	:	6.84 E-02	339	7.71 E-02	114
25	:	8.62 E-02	269	7.71 E-02	72.7
27	:	5.74 E-02	231	3.64 E-02	13.9
29	:	3.50 E-02	141	4.46 E-02	287
31	:	4.70 E-02	89.7	4.16 E-02	252
33	:	2.81 E-02	51	1.86 E-02	187
35	:	1.99 E-02	308	2.58 E-02	100
37	:	2.73 E-02	261	2.22 E-02	64
39	:	1.56 E-02	210	1.32 E-02	336
41	:	1.74 E-02	119	2.11 E-02	277
43	:	1.90 E-02	83.5	1.50 E-02	242
45	:	9.49 E-03	18.9	1.07 E-02	147
47	:	1.49 E-02	295	1.65 E-02	105
49	:	1.45 E-02	276	9.03 E-03	94.5
51	:	2.14 E-03	270	4.78 E-03	244
53	:	9.25 E-03	67.5	1.18 E-02	238

Listing continues for 511 points.

> ZE
Y AXIS: SPECTRAL: 4.94 E-04 TIME HIST.: -10.1

> FS
Y AXIS: SPECTRAL: 1.56 TIME HIST.: 6

X AXIS: SPECTRAL: 2000 TIME HIST.: 256

> ZE
Y AXIS: SPECTRAL: 4.94 E-04 TIME HIST.: -10.1

> PL WP TI
RAISE PLOTTER PEN

>
LOWER PLOTTER PEN

>

>

PC TI
VALUE 0

RAISE PLOTTER PEN
LOWER PLOTTER PEN

> PC TI
VALUE 4

RAISE PLOTTER PEN
LOWER PLOTTER PEN

> PC TI
VALUE -3.5

RAISE PLOTTER PEN
LOWER PLOTTER PEN

> AU
> GO

OK

>

MAJOR WANT LINES < 33% TOTAL

% OF MAJOR LINES < 2 * NOISE LEVEL = 7.45

GO TO 1/8 LEVEL? Y/N: Y

TIME HISTORY

OF LINES = 512
 BANDWIDTH (HZ) = 2000
 PULSE DURATION = 45
 XDUCCER SENS. = 54.1

N	MAG(N)	MAG(N+1)	MAG(N+2)	MAG(N+3)	MAG(N+4)
1	-.364	-.485	-.485	-.485	-.364
6	-.485	-.364	-.485	-.364	-.485
11	-.243	-.605	-.121	-.485	-.364
16	-.605	-.243	-.364	-.364	-.605
21	-.364	-.364	0	-.485	0
26	-.364	-.121	-.485	-.121	-.485
31	-.121	-.485	-.243	-.364	-.243
36	-.605	-.243	-.605	-.243	-.485
41	-.364	-.364	-.243	-.121	-.121
46	-.121	0	-.121	-.121	-.121
51	-.121	-.121	-.121	-.243	-.121
56	-.121	-.121	0	0	0
61	-.243	-.121	-.243	-.121	-.121
66	-.243	-.121	0	-.121	0
71	-.121	-.121	-.243	-.121	0
76	0	-.121	-.121	0	-.243
81	-.121	-.121	-.121	-.121	-.121
86	-.121	-.243	-.121	0	-.121
91	-.121	-.243	-.243	-.243	-.121
96	-.364	-.243	-.364	-.121	-.364
101	-.243	-.605	-.121	-.485	0
106	-.485	-.121	-.485	-.243	-.364
111	-.243	-.485	-.121	-.485	-.243
116	-.605	-.243	-.485	-.121	-.485
121	-.243	-.364	-.121	-.364	0
126	-.243	-.243	-.243	-.121	-.243
131	-.243	-.243	-.121	-.243	0
136	-.121	0	-.121	0	0
141	-.121	-.121	-.121	0	-.121
146	-.243	-.121	-.121	-.121	-.243
151	-.121	-.243	0	-.121	0
156	-.121	0	-.121	-.121	-.243
161	0	-.364	0	-.121	-.121
166	-.121	-.121	-.121	-.121	-.121
171	-.121	-.121	-.243	0	-.121
176	-.121	-.121	0	-.121	-.121
181	-.121	-.121	-.121	-.121	-.121
186	0	-.121	0	-.121	-.121
191	-.121	0	-.121	0	-.121
196	-.243	-.243	-.121	0	-.364
201	-.121	-.121	0	-.243	-.243
206	-.121	-.121	-.121	0	-.243
211	-.121	0	0	-.243	-.121
216	-.121	-.121	-.121	-.121	-.121
221	-.121	-.121	0	-.121	0
226	-.121	0	-.121	-.121	-.121

"Listing continues until N = 1536"

% OF MAJOR LINES < 2 * NOISE LEVEL = 4.48

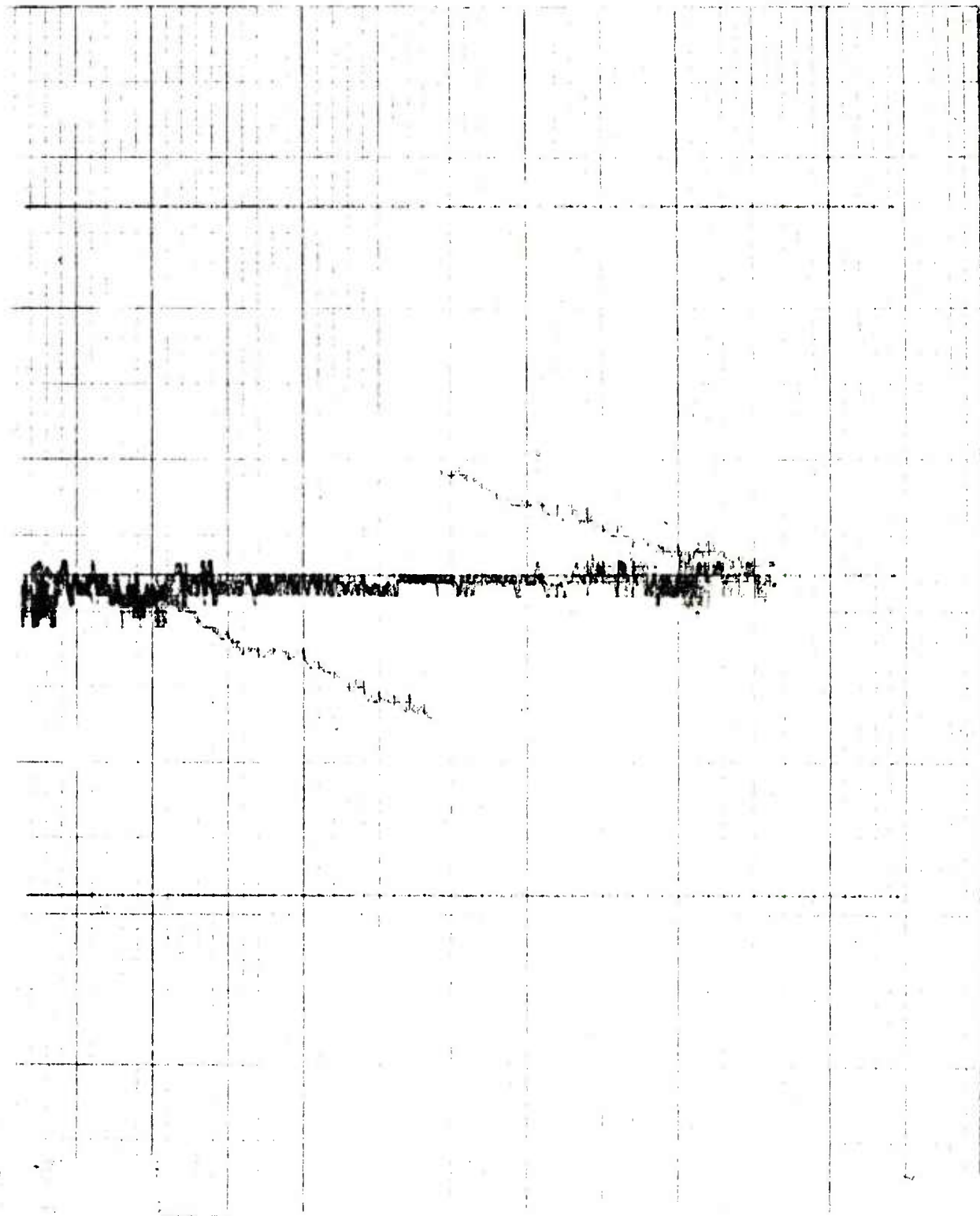
LOWLEV PULSE # 1
 LOWLEV PULSE # 2
 LOWLEV PULSE # 3
 LOWLEV PULSE # 4
 LOWLEV PULSE # 5
 LOWLEV PULSE # 6
 LOWLEV PULSE # 7
 LOWLEV PULSE # 8
 LOWLEV PULSE # 9
 LOWLEV PULSE # 10

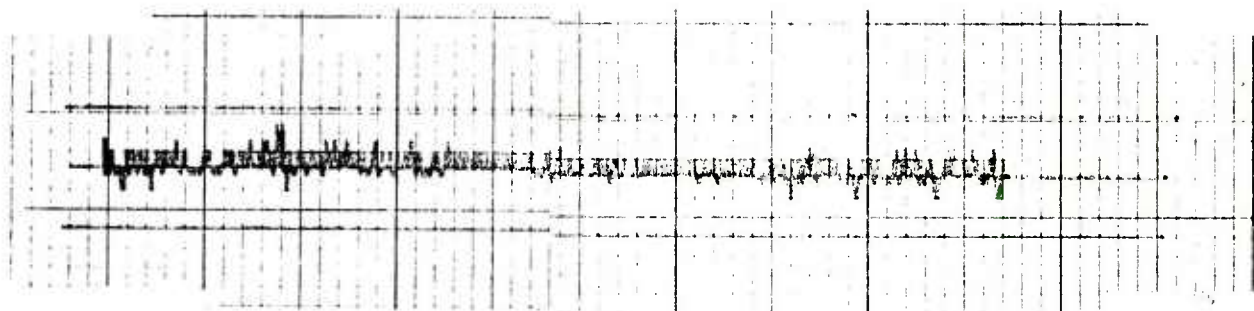
LOW LEVEL EQUALIZATION COMPLETE

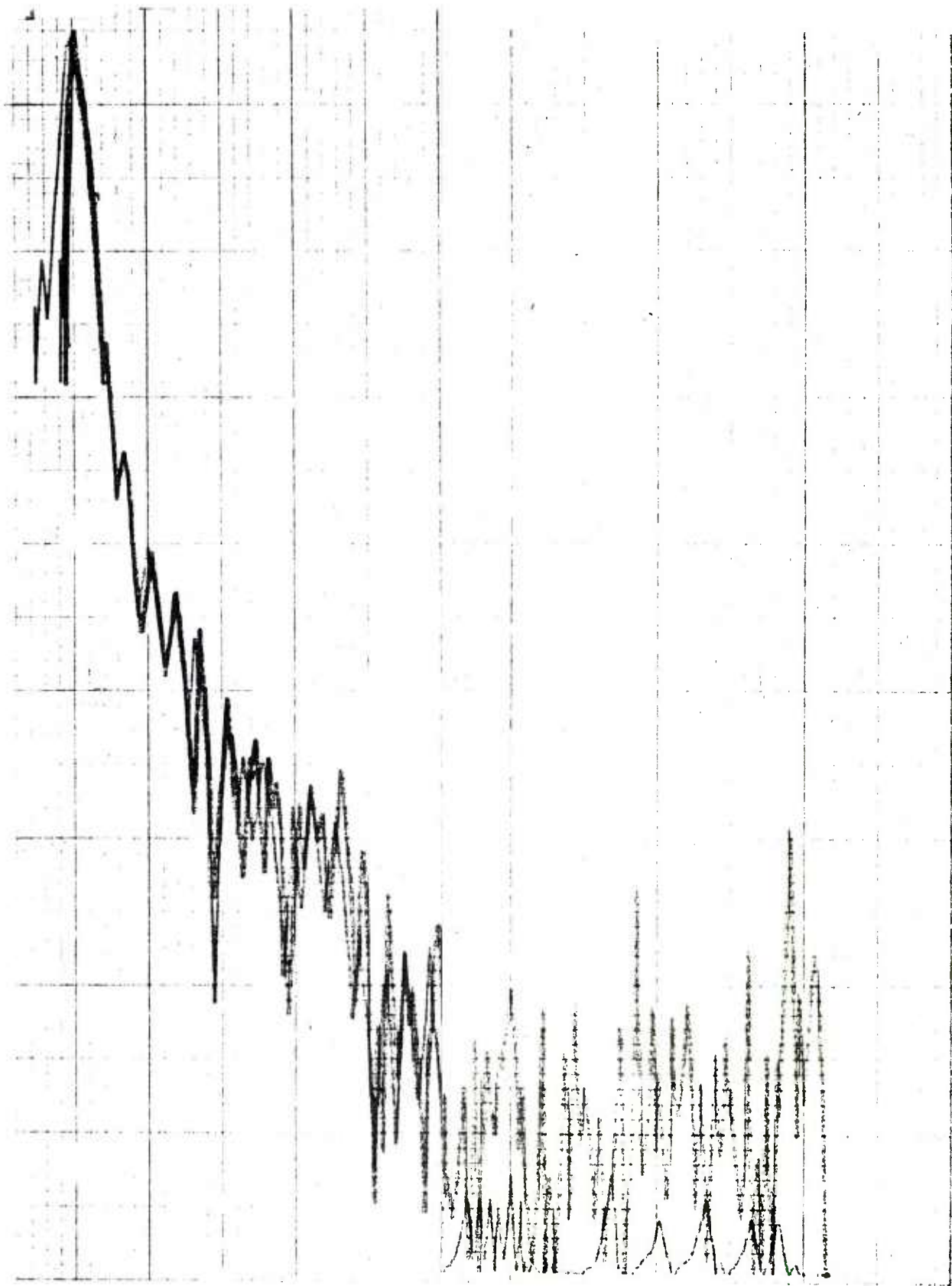
LEVEL	PEAK	TYPE	TIME	BANDW	DEL FRQ	SENS.
1/4	1	SPEC	45	2000	3.91	54.1

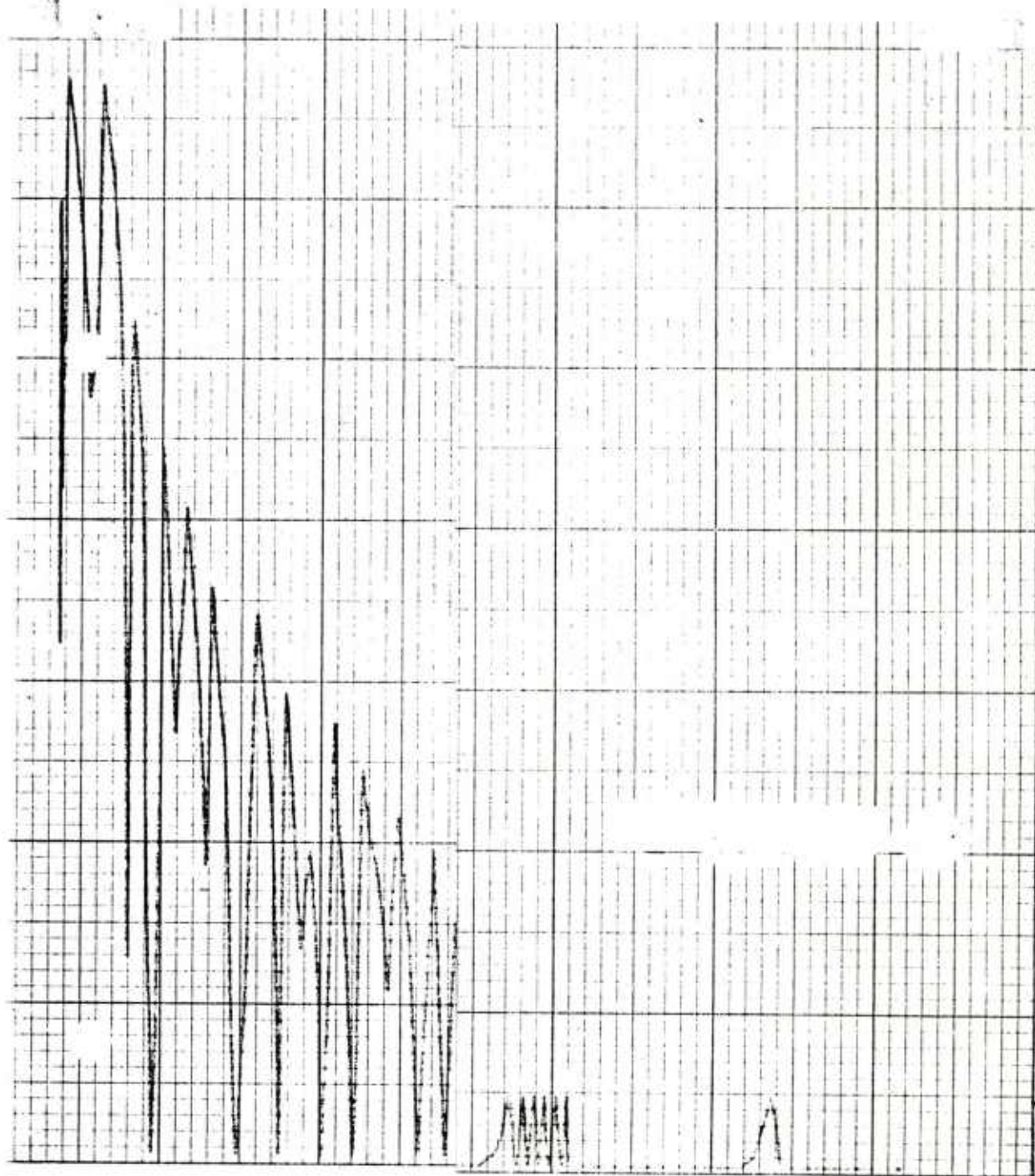
PULSE #	PK RESP	NOTE	% VARIANCE	NOTE
MEAN SPEC	MEAN GEN	MEAN ERR	STD DEV GEN	STD DEV ERR
1	1.06	OK	2.43	OK
-1.48 E-02	-2.46 E-02	9.80 E-03	.207	3.09 E-02
2	.971	OK	1.64	OK
-1.48 E-02	-2.51 E-02	1.03 E-02	.199	2.54 E-02
3	1	OK	1.58	OK
-1.48 E-02	-2.56 E-02	1.08 E-02	.199	2.49 E-02
4	1	OK	1.64	OK
-1.48 E-02	-2.06 E-02	5.69 E-03	.196	2.54 E-02
5	1	OK	1.49	OK
-1.48 E-02	-2.01 E-02	7.29 E-03	.199	2.42 E-02
6	1	OK	1.37	OK
-1.48 E-02	-2.23 E-02	7.51 E-03	.198	2.31 E-02
7	1	END	1.41	END
-1.48 E-02	-2.29 E-02	8.15 E-03	.197	2.35 E-02

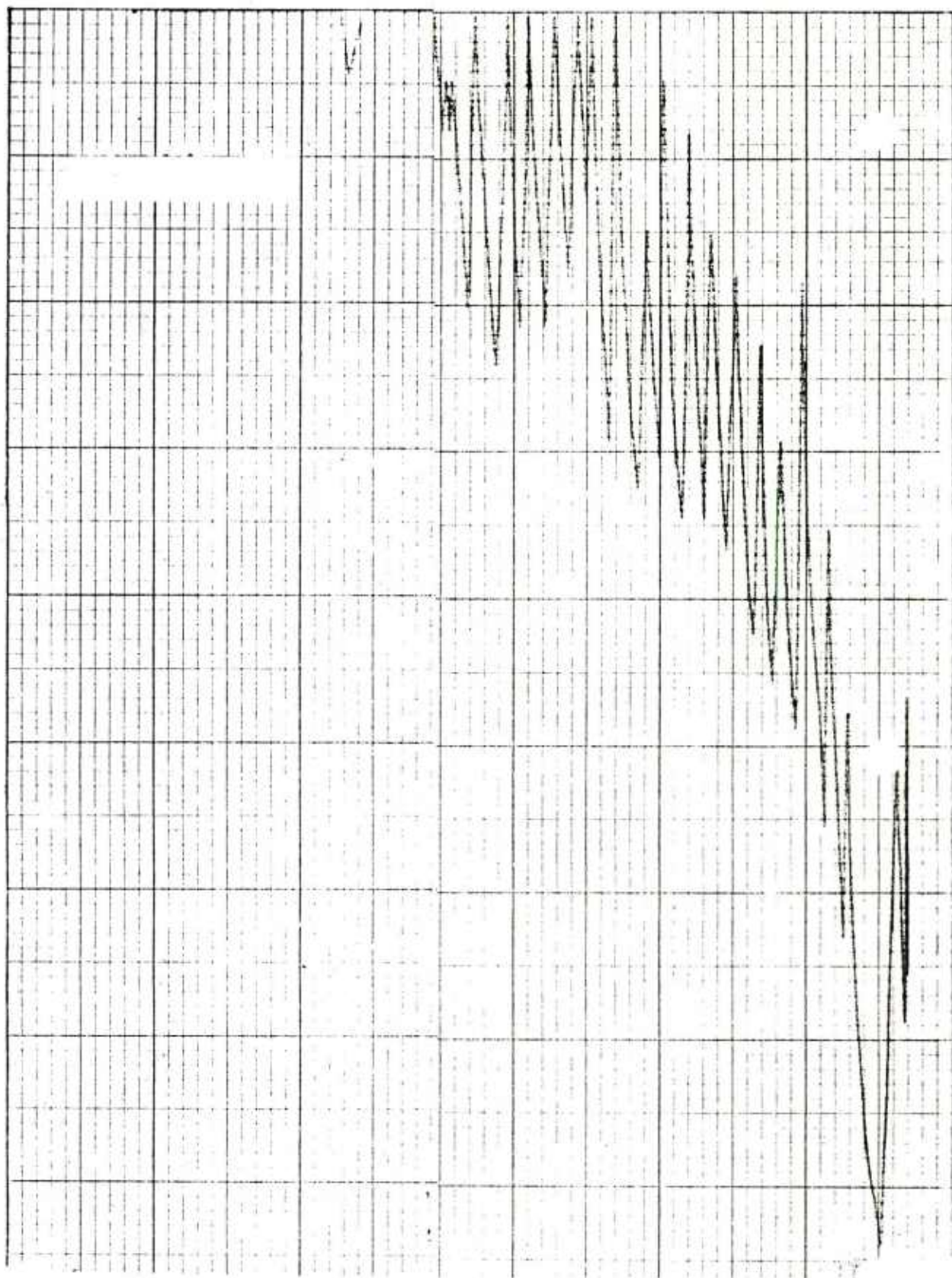
> PL GO TI
 RAISE PLOTTER PEN
 >
 LOWER PLOTTER PEN
 >
 > PL IN TI
 RAISE PLOTTER PEN
 >
 LOWER PLOTTER PEN
 >
 > PR GO TI

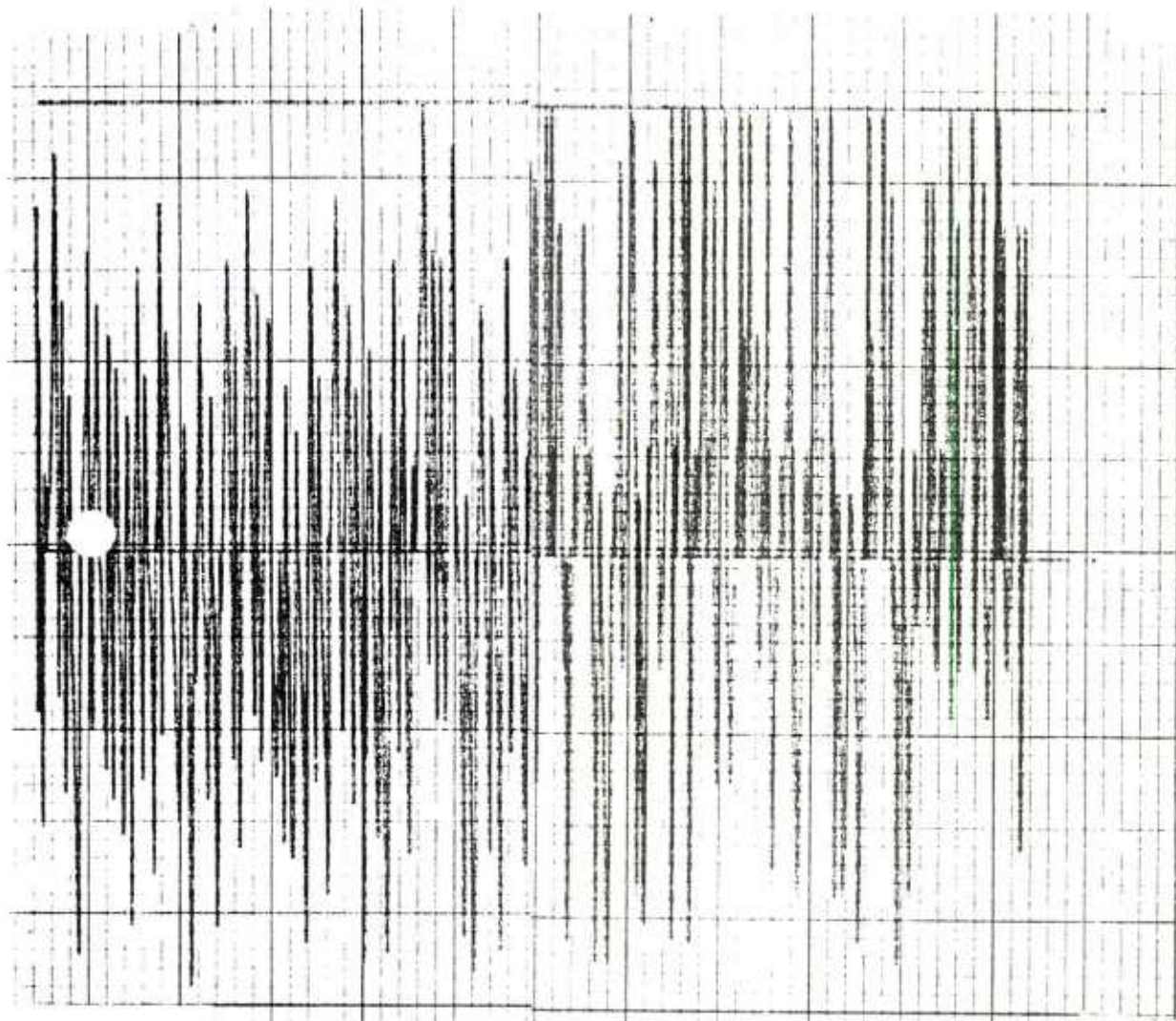












II-3. TEST APPLICATIONS AND RESULTS

II-3.1 Test Requirements and Parameters

Section II-3 contains test results for a variety of test transients synthesized on a vibration shaker using the HDL TWC program. The tests were performed to establish the adequacy of the TWC method in executing field-related and MIL-STD types of transients often specified for military applications--such as for missile fuze production lot acceptance tests, engineering control sample testing, etc. Table III-3 (Ch III) summarizes the types of tests selected. The table contains classical pulses often specified in MIL-STD-331A/-810C, such as half-sine or terminal peak sawtooth, as well as other useful pulses, such as square and exponential decay modes, often used to test for constant acceleration or specimen behavior under impulsive or decremental loading. Of special interest are two field-related complex transients recorded for the PATRIOT missile fuze in the radial and axial directions (simultaneously) during launch environments. These field data were recorded at station 153 of the missile, which is within approximately 2 in.* from the mounting supports of the fuze. (Refer to tables III-3 and -4 and figure IV-8 for a description of these service-related environments.) The test technique is flexible enough that it could produce the actual input into the support structure of the PATRIOT missile fuze had these data been known, providing the test data were within test equipment limitations (which, for all intents and purposes, are similar to the data shown in figure IV-8 and therefore reproducible within the constraints described herein).

II-3.2 Method of Input of Transient Waveform

II-3.2.1 Classical Pulse Description

Classical pulses of the type specified in MIL-STD-810C/331A (i.e., half-sine or terminal peak sawtooth), or other one-sided pulses which can be easily constructed mathematically, such as a square or exponential decay pulse, can be expeditiously programmed on the control system. These pulses can be programmed during the pulse definition phase (of pulse synthesis) by specifying, through keyboard commands, the pulse type (i.e., half-sine), amplitude (g), duration (ms), resolution (number of lines), bandwidth (Hz), etc., as shown in Chapter IV of this report. Using this information, the pulse definition routine within the TWC software quickly constructs the mathematical representation of the pulse. Typically, this process can be accomplished in a few minutes.

*Six inches relative to full-scale development and production configuration.

This approach has been used to define all classical/ single-sided pulses executed in the test program described herein. Pulse parameter(s) can subsequently be retained in a data file (on the system disc), thereby creating a permanent record of the specified pulse. If subsequent replay of the pulse is required, the data file is recalled and the pulse is loaded into the system memory ready for execution with no further programming required.

In fact, any transient or components thereof, whose representation can be expressed mathematically in a closed analytical form, can be efficiently programmed in memory during the pulse definition phase. All that is required is the machine programming of the detailed mathematical representation of the transient, a procedure that need be performed only once. Subsequent use of this representation capability requires the operator only to specify the basic pulse parameters such as amplitude, duration, frequency, delay, etc. This is apparent from the expression that is used to construct a complex harmonic transient bounded by exponential decay due to damping, such as $x(t)$ below;

$$x(t) = \sum_{n=1}^m A_n e^{-2\pi f_n \xi_n (t-t_n)} \sin [2\pi f_n (t - t_n)] ,$$

where

A_n = Peak amplitude of n^{th} component, units

f_n = Frequency of n^{th} component

ξ_n = Damping factor of n^{th} component

t_n = Time delay for n^{th} component

n = Index $1 \leq n \leq m$

II-3.2.2 Complex Transient-Pulse Description

Transient vibration signatures for missile tactical environments, such as depicted for the PATRIOT missile fuze (fig. IV-8) are complex. Unlike classical or single-sided (one-lobe) pulses, these transients cannot normally be expressed in a closed mathematical form. Attempts to curve-fit the data are too elaborate and will probably prove impractical due to excessive error. Three practical methods exist for reading such transients into the control system memory for the purpose of pulse definition. They are

(a) Single-point input via keyboard: This method allows the operator to enter, via keyboard, sets of X-Y points representing the acceleration-time domain of the data. The data are entered in engineering units after they are scaled from a graph or chart. Obviously, chart resolution, number of points selected, and human fallibility are limiting factors. For a single time-limited data case (say up to 100 points), the method can be used quite effectively and with minimum investment in pre-processing.

(b) Single-point input via data tape: A more practical means of inputting the transient(s) is to first specify its X-Y coordinates (in engineering units) on a data tape, then read the tape in on a high-speed reader. This approach was put into use in this test program when defining the vibration transients for cases 1 and 2 (table III-3 and figure IV-8). The original data available on an 8- x 10-in.-size chart were magnified to an 18- x 24-in. format and the curve highlight data traced selectively by a digitizing pen using the HDL DIGITI program. The DIGITI program was used to connect the selected points by straight line segments, then to subdivide the time axis into 10,000 points at equal time increments. These data were then dumped onto a 1-in. wide ASCII paper tape with appropriate header leader information (footnote (b) table III-3). Tapes for several subcases were generated for cases 1 and 2, containing between 300 and 307 data points for the original time covering the transient's range of 20 to 25 ms, as shown in table III-4. This pulse representation method, by far more efficient than the method described in (a) above (since it makes available a substantially greater number of points) is still subject to manual operation.

(c) Single-point input via analog magnetic tape: This method is by far the optimum data input mode. The method allows raw field data which had been recorded on magnetic tapes to be fed directly into the control system via the system's analog-to-digital (A/D) converter. Data files of specific field events can be created rapidly, with all test parameters such as sensitivity factors clearly identified so that the transient may be properly calibrated. Once established, the data files can be used for successive testing with no further programming. The only manual input required through the terminal is for overhead and calibration such as to identify the test records or to specify the acceleration-time sensitivity of the signal. Of the three input methods discussed above, this one requires the heaviest investment in terms of programming of the source program.

II-3.3 Test Equipment

Owing to program errors associated with the CSPI/VARIAN 620f-FFT processor (which is part of the HDL/Gilmore Industries model T5021 test control system), circular FFT/IFFT operations, which

represent the main operational feature of the TWC test method, could not be performed. Instead, tests were conducted on the only other known government test control equipment (CPU and peripherals) which was configured to communicate with Gilmore Industries control software. This equipment was at the Navy/Pacific Missile Test Center (PMTTC) at Point Magu, CA. All test results presented herein were derived using this equipment, which is shown schematically in figure IV-9. The 200-lb magnesium plate which was mounted on the shaker to simulate the test payload is well in excess of the payload weight that might be encountered during testing of such HDL-developed missile fuzes as PATRIOT, Chaparral, Lance, GSRS, and others. Note that two accelerometers were used to validate the performance of the control sensor. The transducers used had relatively high sensitivity factors, but this was done to compensate for significant levels of wideband noise noted for the vacuum-tube-type power amplifiers.

II-3.4 Closed-Loop Synthesis of Vibration Transients

In closed-loop operations the vibration shaker and power amplifier are excluded from the pulse control mode (the output and input signals are shorted out, thus preventing any forward or feedback excitation). This condition permits the full exercise and testing of the internal synthesis capabilities of the TWC software, and allows validation of the quality of the program by ultimately comparing the error spectrum between the internally synthesized and specified transients.

Table III-1 contains a summary of the pulses/transients which have been synthesized in closed-loop using the test equipment described in II-3.3. Also shown in the table is the corresponding overall variance error for each of the synthesized transients. All transients have been synthesized at the specified full level. With few exceptions, the overall variance error (as defined by eq II-10) turned out to be extremely small--i.e., less than 1 percent. The maximum error (5.13 percent) was noted for an extremely short pulse (0.25 ms half sine). The reason(s) for this error and others of lower magnitudes (cases 1 and 2) are presented below, along with the synthesis operations for each pulse. Note that for cases 1 and 2, in spite of the complex nature of the transients, the variance error obtained was quite reasonable. This suggests that other such transients, which are based or derived from actual field environments, could also be synthesized at similarly low error (i.e., within 1 to 3 percent), thus validating the practicability of the TWC test method.

A graphical representation of the specified, synthesized, and resulting overall error in the time domain for each of the transients included in table III-3 is presented in figures IV-10 to -22. The WANT and GOT nomenclatures used by the software correspond to

the specified and synthesized transients, respectively. The error display (ER) represents amplitude differences in the time domain between the prescribed and synthesized transients.

The time transients for cases 1 and 2 were specified by approximately 300 data points (see table III-4) coded on a 1-in. data (paper) tape. However, several difficulties were encountered in attempting to read these data tapes into the computer. The data coded onto the data tapes allowed for 3-place accuracy (i.e., .xxx, x.xx, xx.x), but the TWC software allowed 2.5-place accuracy. Thus, data points specified above 10.0 ms were beyond the capability of this software. This condition necessitated truncation and rounding off of the original data. Note that for the 0.066-ms resolution desired (5000-Hz sampling rate), two entries, such as 9.93 ms and 10.066 ms, both appear to the software when converted to internal form, as a single-valued point at 10 ms; this is obviously erroneous, because two acceleration levels cannot exist at the same time. Numerous points have been deleted and new data tapes were created, at which time it was noted that the new data tapes resulted in a net negative area bounded by the time transient. (Presently, the TWC software will compensate only for net positive area.) Finally, several acceleration slopes (rate of increase or decrease between any two points, usually a peak/valley combination) were far too great to be replicated by the control and therefore had to be deleted. For the type of data included in cases 1 and 2, it was noted that at least four data points per peak/valley combination should exist if the dynamic range of these data exceeds 50 percent of the maximum acceleration level specified. Furthermore, the digital control scheme cannot possibly replicate a transient where every point that it drives is fully constrained and prespecified unless it has a perfect servomechanism. However, digital controllers, regardless of their design, are interactive approximators; for this reason, it was noted for the data under consideration (cases 1 and 2) that a minimum of 5 time points per peak/valley data excursion would suffice for adequate manipulation of the servomechanism controller. As a result of the observation/reasons specified above, case 1-1 was approximated by a 55-point description of the acceleration transient and case 2-1 by a 25-point approximation. Some of the data points entered were inserted to compensate for the negative net area. The oscilloscope record (fig. IV-23) clearly displays these new data points selected to describe case 1-1.

Since the acceleration levels for the desired transients ranged between 7.7 and 100, it was necessary to select accelerometer sensitivities such that the resultant voltage in the feedback path would be between 2 and 4 V at full level (which is the optimum range for the

servomechanism controller). Note that for this range, pre-equalization at 1/8 the level results in a signal feedback voltage level between 250 and 500 mV, yielding a signal-to-noise ratio of 25 to 30 dB. The following is a discussion of the results obtained during closed-loop synthesis, pulse by pulse.

(1) Case 2-1: The percentage of variance after 10 full-level pulses was 2.38. The actual description is included for the 25 points used; CRT hard copy output is included showing the specified (WANT) and synthesized (GOT) transients, respectively. Also included is the ER plot displaying amplitude differences in the time domain between WANT and GOT.

(2) Case 1-1: The percentage of variance after 10 full-level pulses was 3.5. The 55 points used and the manner of reduction from the original 300 points are described. CRT hard copy output includes the WANT, GOT, and ERROR display in the time domain. The WANT spectrum in polar representation indicated the decibel range of the pulse description to be less than 40 for the bandwidth employed, and the WANT phase display shows no discernable pattern as is usually seen in classical pulses.

(3) Half-sine, 5 ms, 100 g: The percentage of variance after 10 full-level pulses was 0.0745. The CRT output includes the WANT, GOT, and ERROR displays.

(4) Half-sine, 20 ms, 15 g: The percentage of variance after 40 full-level pulses was 0.222. CRT hard copy output includes WANT, GOT, and ERROR arrays.

(5) Half-sine, 0.25 ms, 50 g: The percentage of variance after 10 full-level pulses was 4.97. A 0.25-ms time duration is legibly definable, but even at a 5000-Hz sample rate there exist only 3.75 points available for pulse definition (practically speaking, only 3 points). Normally, if there are less than 10 points available to generate the pulse it would be rejected by the software (certainly less than 10 could not be replicated at the shaker, regardless of closed-loop capability). Observing the CRT hard copy of the WANT array one notes pre- and post-oscillations in the defined pulses resulting from an insufficient number of time points in the pulse body. These additional short-duration pulses were executed for comparison:

Half-sine, 0.7 ms, 50 g, 5000 Hz, 256 lines: the percentage of variance = 1.09, and

Half-sine, 0.7 ms, 50 g, 4000 Hz, 64 lines: the percentage of variance = 0.110.

CRT hard copy output includes WANT, GOT, and ERROR display arrays for these pulses.

(6) Exponential decay, 3 ms, 100 g: the percentage of variance after the 10th equalization was 0.0747.

Exponential decay, 50 ms, 10 g: the percentage of variance after the 10th equalization was 2.26. The CRT hard copy output for these pulses includes the WANT, GOT, and ERROR displays.

(7) Terminal peak, 6 ms, 75 g: the percentage of variance after the 10th equalization was 0.115. Terminal peak, 11 ms, 30 g: the percentage of variation after the 6th equalization was 0.280. The CRT hard copy output for these pulses includes the WANT, GOT, and ERROR displays.

In general, the test system using the TWC software was found capable of adequately replicating the prescribed pulses within a reasonable percentage of variance. The replication of the half-sine 0.25-ms pulse was somewhat poor as a result of an insufficient number of points available for pulse description. It was also noted that after a few low-level equalization attempts (1/8 level), the first quarter-level pulse was equalized well within the specified (10 percent) variance, and usually did not significantly improve thereafter. After observing oscilloscope records during low-level equalization attempts, it was noted that very little improvement was obtained after the third or fourth equalization attempt.

II-3.5 Transient Synthesized on Vibration Shaker (Open-Loop Operation)

Prior to testing it was noted that noise produced by the vacuum-tube type of power amplifier which drives the shaker produced vibration levels of about 3 g. This condition existed even when the drive signal from the digital control system was disconnected, and the input to the power amplifier was shorted to ground. The frequency content of this noise was not of any predominant frequency as observed on an oscilloscope screen. In addition, a randomly occurring beating or ticking noise was also detected for the shaker. The magnitude of these noise components or "spikes" was substantially greater than 3 g and is clearly evident for the synthesized half-sine pulse (50 Hz, 6 ms--fig. IV-25(a)). For pulses whose 1/8 or 1/4 level was barely higher than the constant noise level, or for the case where the high-level vibration spikes occurred while the pulse was being synthesized on the vibration shaker, equalization was not possible since program "FFT overflow" conditions would result, thereby aborting the equalization process. These conditions developed for the following transients: (1) 15 g, 20 ms, half-sine, (2) 10 g, 18 ms², (3) 30 g, 11 ms, terminal peak, (4) 10

g, 50-ms exponential decay, and (5) case 2 (PATRIOT missile fuze/radial direction launch environments). For the latter transient (case 2), the peak acceleration level of approximately 7.5 g represented a signal-to-noise ratio of almost 2:1 (as a maximum) with respect to the constant noise level of approximately 3 g. (Note that anywhere else in the data region the amplitude is less than 7.5 g, resulting in an even lower signal-to-noise ratio.) Obviously no low-level shock transient can be effectively synthesized on a shaker at such low signal-to-noise ratios.

Note that the above deficiencies, which prevented the synthesis of transients that had already been adequately synthesized in closed-loop operation, were inherent to the specific shaker/power amplifier available to conduct these tests (see fig. IV-9). That is, the TWC method was not deficient, as borne out by the test results and correspondingly low variance error shown in table III-2. Had a low-noise solid-state power amplifier been available during the tests, it is expected that all the aborted cases would have been executed with overall variance error well below 10 percent.

The frequency response of the test excitation equipment (see fig. IV-9) was poor below 10 Hz, and the ability to respond to wideband excitation was somewhat deficient. Since the spectral representation of a half-sine pulse yields several lobes of descending magnitude, given the proper time duration for the pulse within a drive data frame, the principal lobe (which might be an order of magnitude higher than successive lobes) might contain an insufficiently small number of spectral lines. This insufficiency, coupled with the fact that the entire dynamic range has been allocated to the replication of the primary spectral lobe, saturates the system and prevents proper pulse replication (either due to abort condition or excessive error). Indeed, for the 100-g 6-ms half-sine pulse the test system was aborted under the diagnostic ABORT, GAIN OUT OF RANGE, whereas the 30-g, 11-ms terminal peak pulse was aborted due to variance error in excess of 60 percent. Another cause aborting the above half-sine pulse was the velocity limitation of the vibration shaker.

For the 50-g, 0.25-ms half-sine pulse, the shaker was noted to have been physically restrained by the travel stops in an attempt to draw enough dc shift (offset) to result in zero terminal velocity and displacement. Consequently, the system would not pass the 1/8 equalization level. The time duration of this pulse was increased to 0.7 ms, but equalization could still not be achieved beyond the 1/4 level due to physical stopping of the shaker (confirmed acoustically by communication heads placed on the shaker). Table III-2 presents a summary of the transients that have been successfully synthesized. For cases where full levels were not met, limiting factors such as those noted above were the constraining parameters. With one exception, the

overall percentage of variance (based on the relationship shown in eq. 10) was below 10 percent. Successive attempts to iterate on the transient (i.e., tenth attempt instead of fifth attempt) did not necessarily improve the result, thus indicating that the fifth attempt resulted in stable equalization. Figures IV-23 to -28 present the CRT results of the transients as replicated on the vibration shaker along with the corresponding amplitude variance error (showing component-by-component comparison between the specified and synthesized transient). Both displays are presented in the time domain, with the amplitude given in units of g and the time scale in units of milliseconds. The plots were generated using the plotting package of the test system TWC software.

Of particular interest is the replication signature for the PATRIOT missile fuze axial launch environment (case 1-1, fig. IV-23(a)). In spite of its complex nature, this signature was replicated within 7 to 8 percent of the specified transient, indicating the capability of the TWC method to replicate complex service environments on a laboratory vibration shaker. In the past, environments of this nature could be produced only during actual missile launch conditions, a costly and lengthy procedure, considering all necessary setup operations. An oscilloscope record of the PATRIOT axial launch signature (case 1-1) is presented in figure IV-24. The record was taken by a Polaroid camera whose film was exposed to the synthesized signal as displayed on the CRT screen (the oscilloscope was triggered externally by the synthesized signal). Only 22 ms of a total of 25 ms of data are shown due to the low level of the signal, which did not trigger the oscilloscope until 3 ms into the event. Double exposures were taken by opening the shutter once for each pulse (for each of the pulses shown). Note the point definition used to describe the pulse, and the excellent repeatability of the data which shows practically no deviations for the complex transient, which has been synthesized repeatedly for up to 50 times at full level. This example vividly demonstrates the reliability of the TWC method in replicating complex field-related service environments characteristic of missile fuzes.

Chapter III.--TWC Validation Testing--Tabulated Data

TABLE III-1. VARIANCE ERROR DURING CLOSED-LOOP SYSTEM SYNTHESIS OF SPECIFIED TRANSIENTS

Pulse type	Amplitude (g)	Time (ms)	Bandwidth (Hz)	No. lines ^a	Overall variance error (%)	Iteration No.	Level of pulse at equalization ^b
Half-sine	100. ^c	6.0	3000.	128	0.08	5	Full
	15.	20.	2000.	256	0.23	5	Full
	50.	0.25	5000.	64	5.13 ^d	5	Full
	50. ^e	0.70	4000.	64	0.011	5	Full
Square	50.	3.0	4000.	64	0.05	5	Full
	10.0	18.0	2000.	256	0.24	5	Full
Terminal peak	75.	6.0	3000.	128	0.13	5	Full
	30.	11.0	2000.	128	0.28	5	Full
Exponential decay	100.	3.0	4000.	64	0.07	5	Full
	10.0	50.	2000.	512	2.48	5	Full
Complex transient							
PATRIOT							
(Fuze) Case 1 ^b --See figure 8,							
Ch IV.		25.	4000.	512	3.34	5	Full
(Fuze) Case 2 ^b --See figure 8,							
Ch IV.		20.	5000.	512	2.28	5	Full

^aBased on equation (9), Ch II.^bFull level pulse is a pulse synthesized at the peak level specified.^cThis pulse was derated from 100 to 50 g. because of shaker velocity limitations and other constraints (Ch II; sect 3.4).^dSystems limits exceeded.^eThis pulse was tried as a substitute for the 50 g, 0.25 ms Hz pulse because of the vibration shaker's frequency response limitations.

TABLE III-2. VARIANCE ERROR FOR TRANSIENTS SYNTHESIZED ON VIBRATION SHAKER

Pulse type	Level of pulse at equalization	Overall variance error (%)	Attempt No.	Variance error (%)	Iteration No.
Half-sine, 6 ms, 100 g	Half	9.28	5	9.75	10
Exponential decay 3 ms, 100 g	Full	1.94	5	1.61	10
Terminal, 6 ms, 75 g	Half	12.6 ^a	5	13.4 ^a	10
Square, 3 ms, 50 g	Full	1.59	5	1.82	10
Case I, No. 1 (PATRIOT missile fuze/axial direction at launch)	Full	7.38	5	8.06	10

^aQuestionable results due to excessive system noise (see pre- and post-pulse trails--fig. 27(a), Ch IV).

TABLE III-3. SUMMARY OF TEST TYPES

Pulse type	Amplitude (g)	Time (ms)	Bandwidth (Hz)	No. lines ^a
Half-sine	100. 15. 50.	6.0 20. 0.25	3000. 2000. 5000.	90 (128) 200 (256) 15 (640)
Square	50. 10.0	3.0 18.0	4000. 2000.	60 (64) 180 (256)
Terminal peak	75. 30.	6.0 11.0	3000. 2000.	75 (128) 110 (128)
Exponential decay	100. 10.0	3.0 50.	4000. 2000.	60 (64) 500 (512)
Complex transient				
PATRIOT				
(Fuze) Case 1 ^b --see figure 8, Ch IV.		25.	4000.	512 (512)
(Fuze) Case 2 ^b --see figure 8, Ch IV.		20.	5000.	512 (512)

^aBased on the relationship $\text{Time} = 0.2 \times 3 \times \text{NL}/3 \times \text{BW}$ with appropriate rounding (shown in parentheses).

^bSeveral data tapes containing various time slices of these time transients are presented in table 2.

Format required for the data tapes is as follows:

LEADER (blank tape), Number of points on this tape, each (time, amplitude) point beginning with $T = 1$, TRAILER (blank tape): $T = 1$ is the first operator-selected nonzero point taken from the origin. This routine assumes that the first data point is always located at the origin (i.e., 0,0 intercept in the acceleration-time plane). Amplitude values are given in units of g , and time values in units of milliseconds. Tape format is ASCII, either HSR or LSR as selected by the monitor program, and each data point is represented by our I16 numeric format. The data tapes are punched, 1-in.-wide paper tapes generated on the system's teletypewriter. The raw data were initially digitized, processed by a computer in accordance with above format, and then dumped on the paper tape. The HDL program used to digitize the raw data is called DIGITI.

TABLE III-4. SUMMARY OF TYPICAL SERVICE-RELATED TEST TRANSIENTS

Case I: (PATRIOT Missile Fuze Vicinity--Longitudinal Direction at Launch

Bandwidth: 4000 Hz

Nominal Sampling Interval = $\frac{1}{3 \times 4000} = 0.08333$ ms

Tape No.	No. of points	Time/point (ms)	Total time duration (ms)
Case 1 -1	300	0.0834	25.02
-2	300	0.0833	24.00
-3	305	0.0833	25.40
-4	305	0.0834	25.44
-5	300	0.0830	24.90

Case II: PATRIOT Missile Fuze Vicinity--Radial Direction at Launch

Bandwidth: 5000 Hz

Nominal Sampling Interval = $\frac{1}{3 \times 5000} = 0.0666$ ms

Tape No.	No. of points	Time/point (ms)	Total time duration (ms)
Case 2 -1	300	0.0667	20.01
2	300	0.0666	19.98
3	305	0.0666	20.31
4	305	0.0667	20.34
5	300	0.0660	19.80

NOTE: Only one test per case was planned for Case I and Case II (for a total of two tests). The tape with the most favorable point-count and sample interval (relative to roundoff errors) shall be selected at the time of test. Each subcase represents a separate tape output from DIGITI program. Data covers essentially same time domain with different round off error.

Chapter IV.--TWC Validation Testing--System Configuration
and Test Results

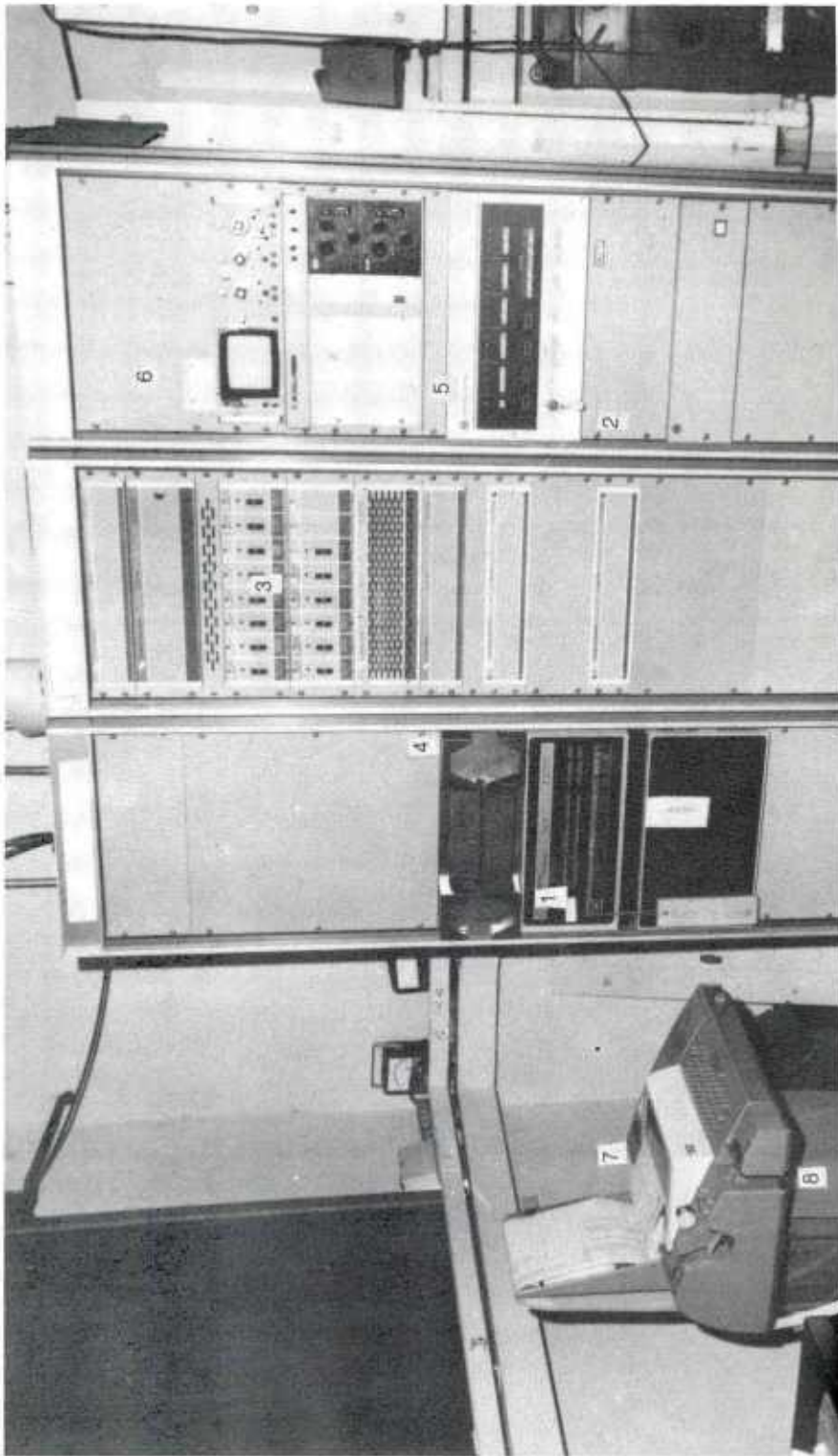


Figure IV-1. HDL computer control for vibration/shock test system:
(1) digital minicomputer controller, (2) minicomputer to generate vibration/shock transients, (3) X-Y plotter (amplitude versus frequency), (4) display oscilloscope, (5) precision gain amplifiers, (6) paper tape reader, (7) teletypewriter terminal, (8) paper tape reader/punch.

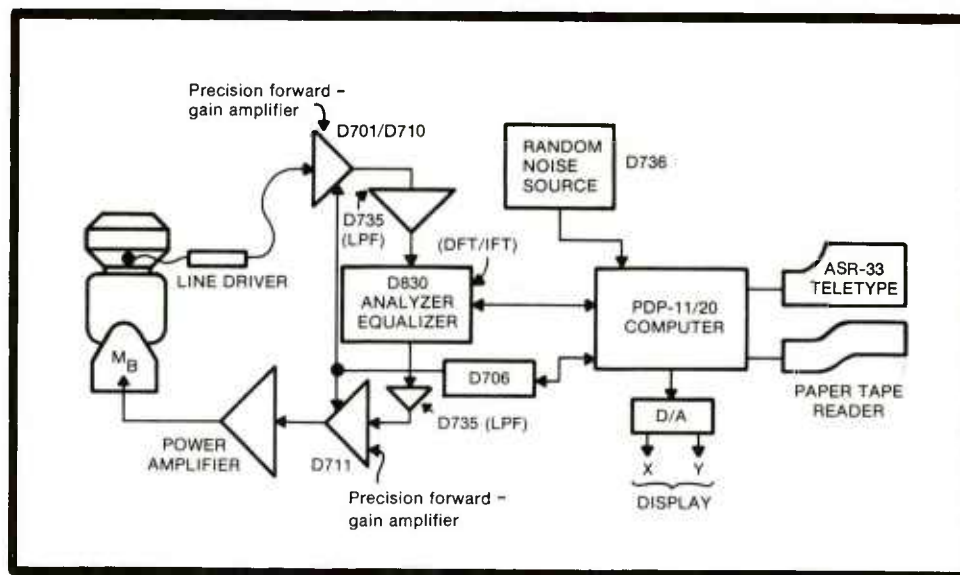
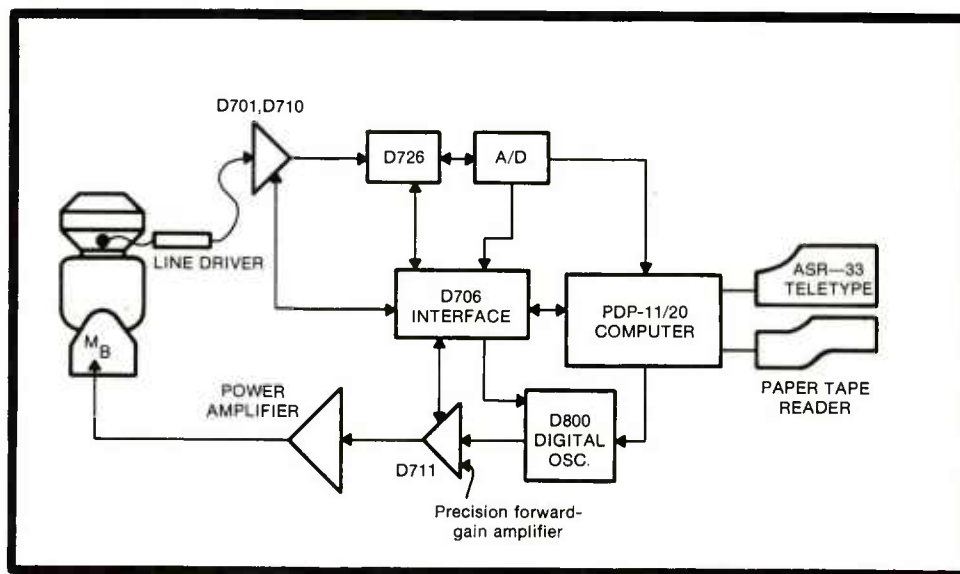


Figure IV-2. Basic T5020 system: (a) sine control, (b) random control.

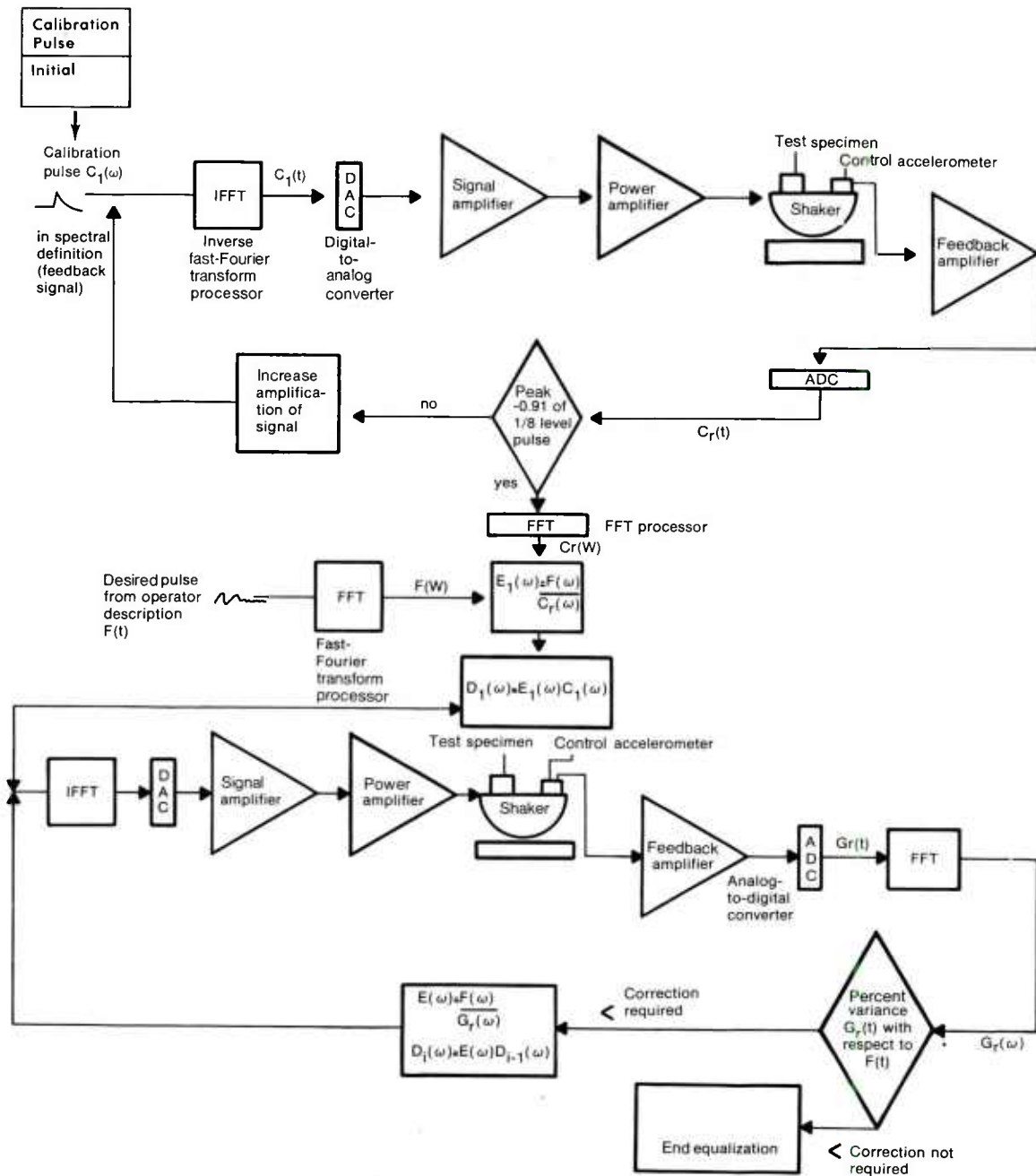


Figure IV-3. Transient waveform control equalization process.

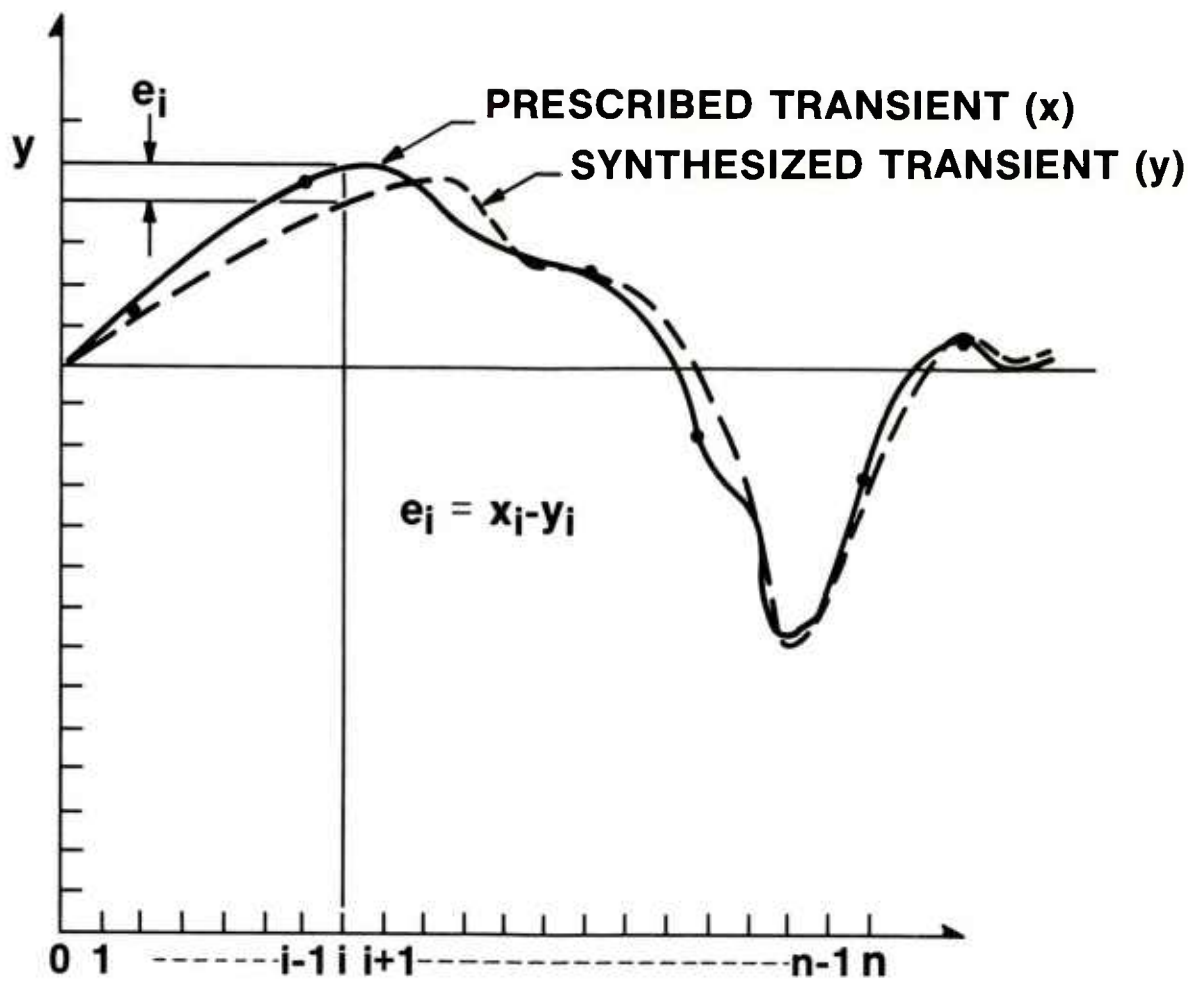
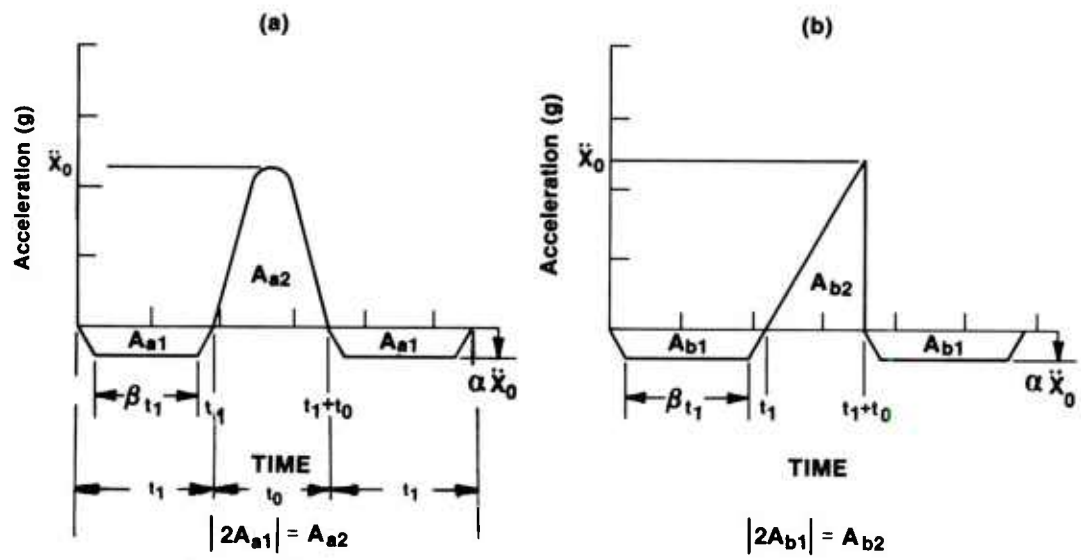
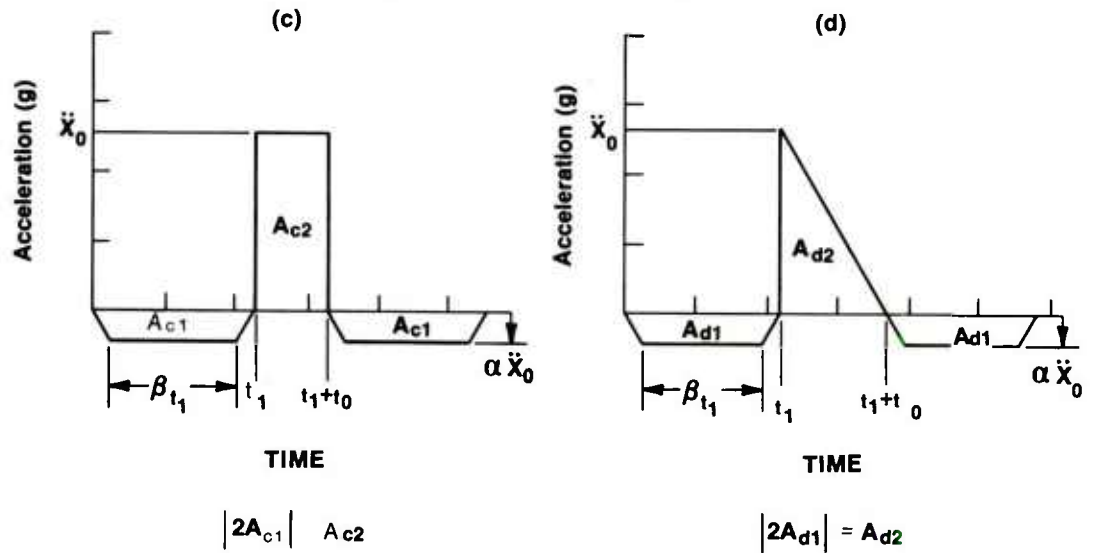


Figure IV-4. Error estimation for the transient waveform control test method.

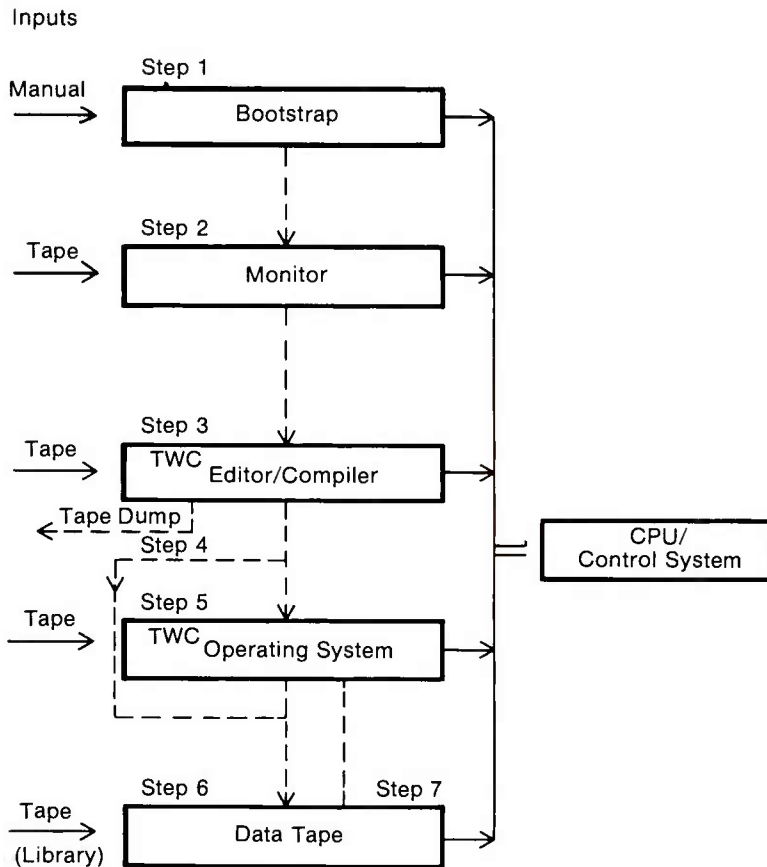


- (a) HALF-SINE
 (b) TERMINAL PEAK SAWTOOTH
 (c) SQUARE
 (d) EXPONENTIAL DECAY



Note: Same time breakdown applies to (b), (c), and (d).

Figure IV-5. Modified classical pulses.



Step 1

Initiates central processor unit (cpu); cpu and memory readied to receive Monitor program.

Step 2

Required to load tape in step 3 and initiate step 4; also for electronic housekeeping; resides permanently in memory. Monitor program is a component of the operating system; it allows for communication with the operator and acts as driver for device input and output.

Step 3

Interactive instructions to prepare data tape (translates converter routines to machine language); performs limit checks on test parameters; codes all test parameters and entries, including waveform description.

Step 4

Initiates operations to create data tape.

Step 5

Specifies type of test to cpu (i.e., TWC); prepares memory to read in data tape. This step controls test execution through cpu and control system hardware.

Step 6

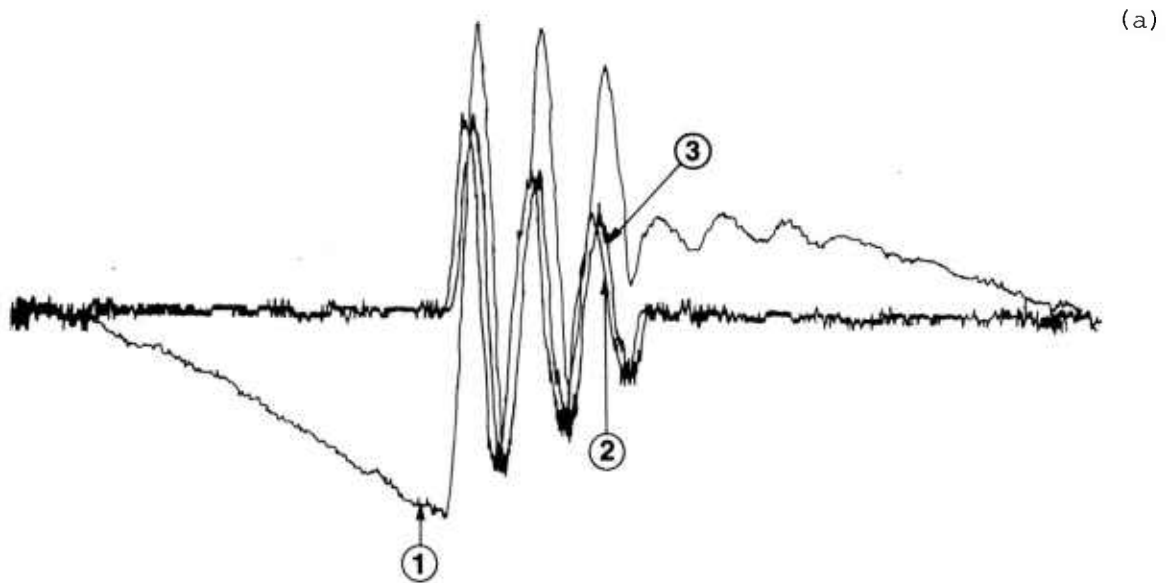
Outputs data--complete test information includes description of test-generated waveform, control parameters, test mode, alarm/abort limits, error criteria, etc.

Step 7

Validated tape loaded/reloaded to execute test.

*Minimum cpu core requirement is 24K-words for data and source programs.

Figure IV-6. Program input/loading procedure to initiate a transient waveform control test.



- ① Drive Signal
- ② Specified Transient
- ③ Synthesized Transient

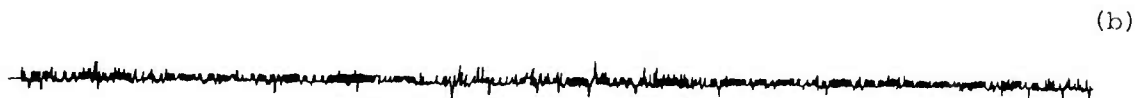
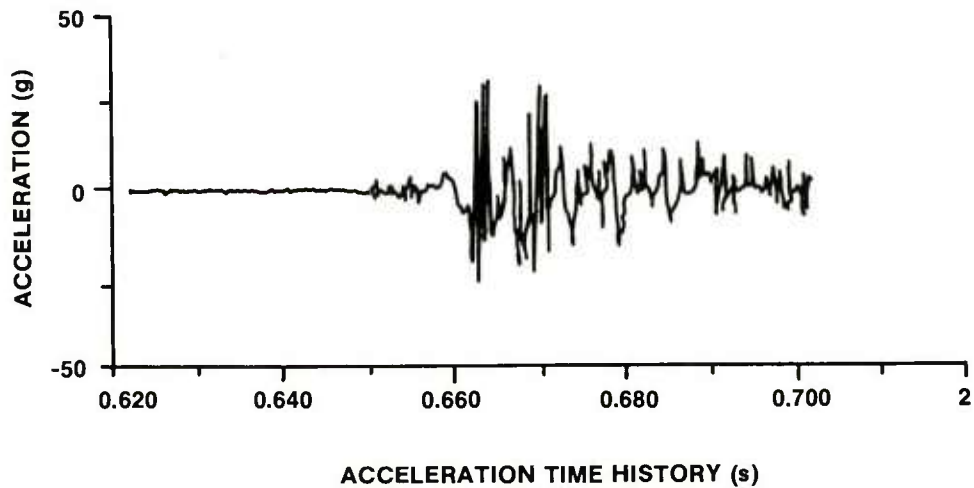


Figure IV-7. Comparison of specified and synthesized transients:
(a) exponential decay transient synthesized on vibration shaker, (b) error between specified and synthesized transient.

Measurement 030260 0.620 to 0.700 s (Time Interval)
Vibration—Forward Mating Ring Station 153 Longitudinal



Measurement 030261 0.647 to 0.708 s (Time Interval)
Vibration—Forward Mating Ring Station 153 Radial

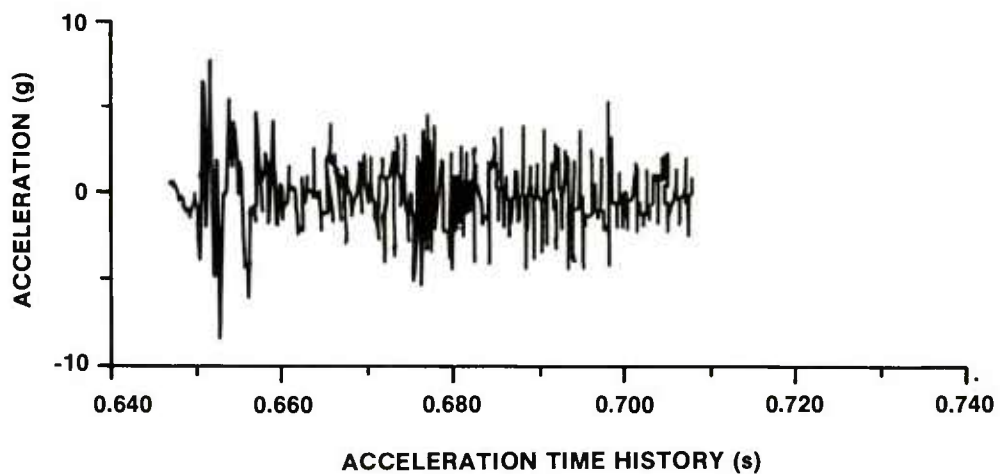


Figure IV-8. Motor ignition transients--PATRIOT missile.

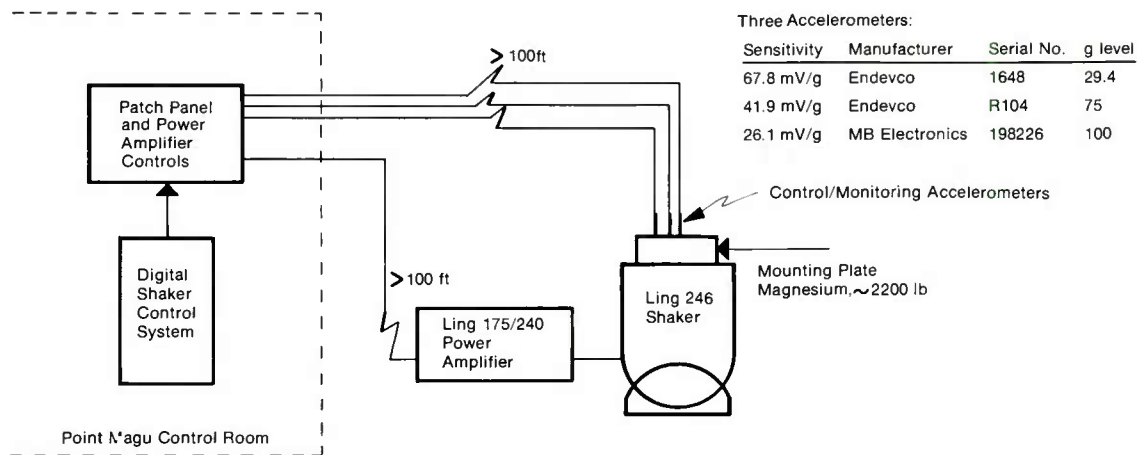


Figure IV-9. System diagram for transient waveform control testing.

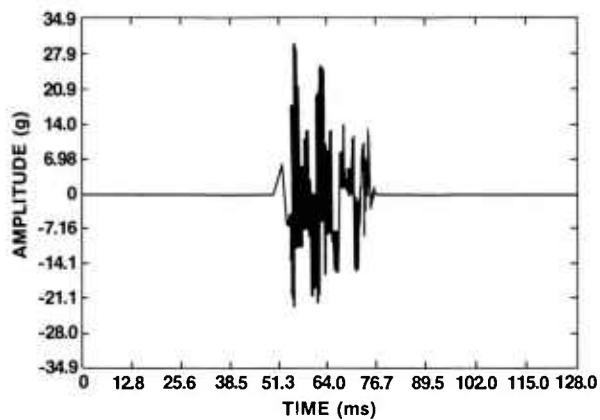
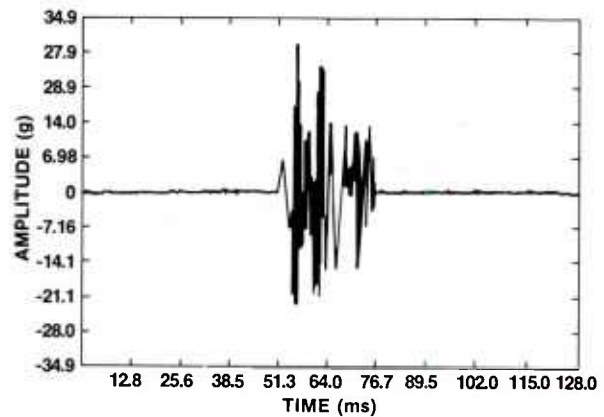


Figure IV-10. Case 1, No. 1:
specified and synthesized
transients--PATRIOT fuze
environment at launch
(station 153, longitudinal).

(a) specified transient: 25 ms,
55 data points, 4000 Hz, 512 lines

(b) as synthesized



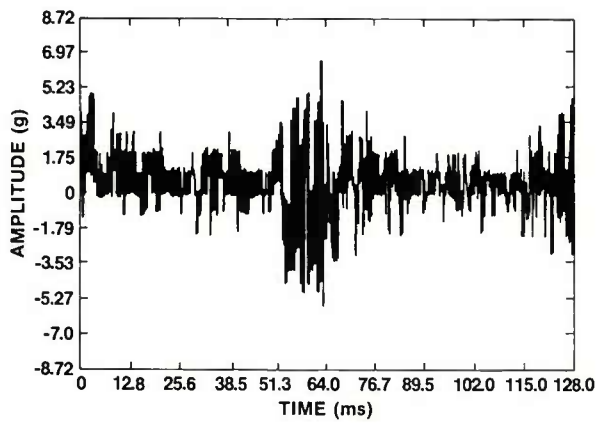
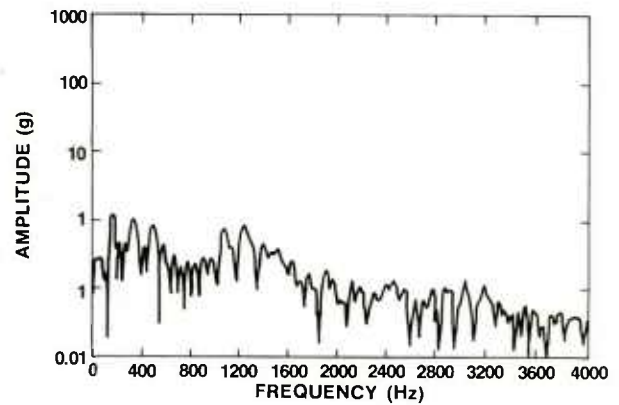
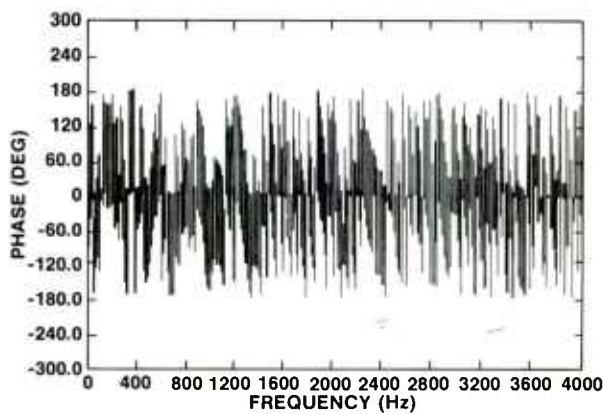


Figure IV-10. (Cont'd) Case 1, No. 1: specified and synthesized transients--PATRIOT fuze environment at launch (station 153, longitudinal).

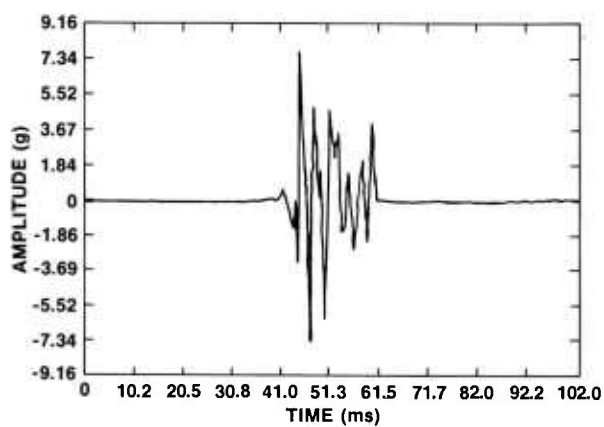
(c) error between specified and synthesized transient



(d) Fourier spectrum for specified transient

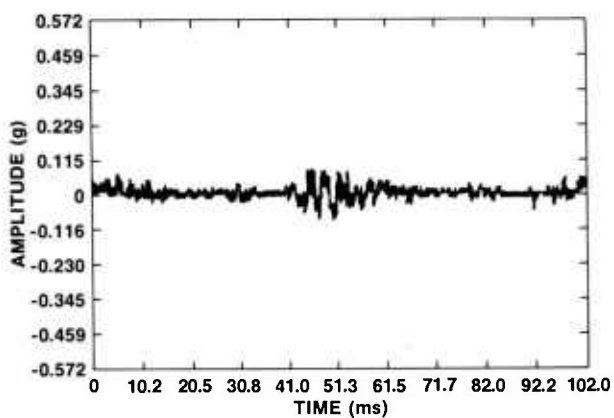
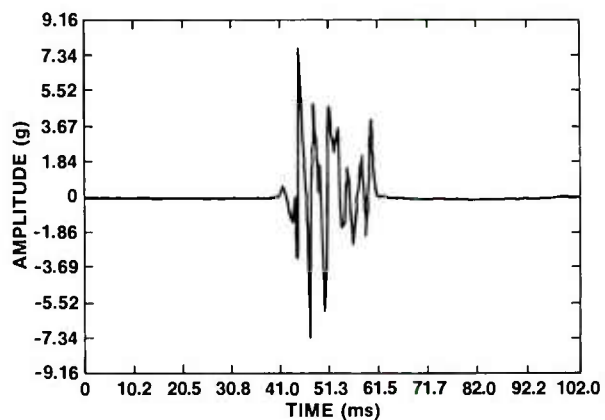


(e) phase spectrum for specified transient



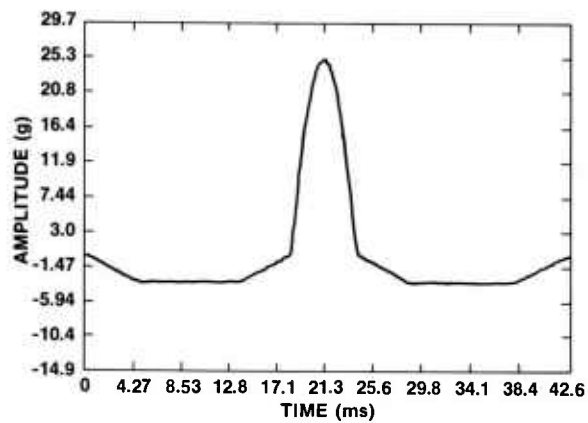
(a) specified transient:
20.5 ms, 25 data points,
5000 Hz, 572 lines

(b) as synthesized

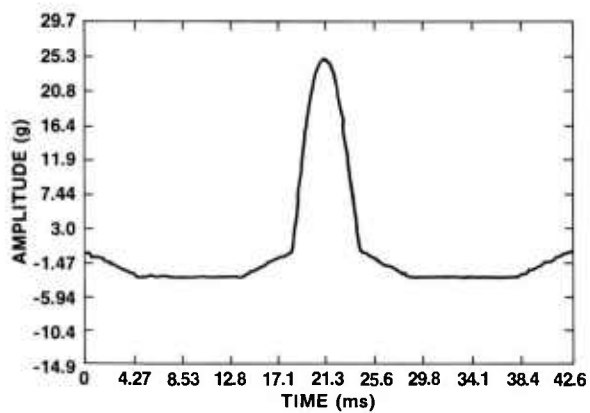


(c) error between specified and
synthesized transient

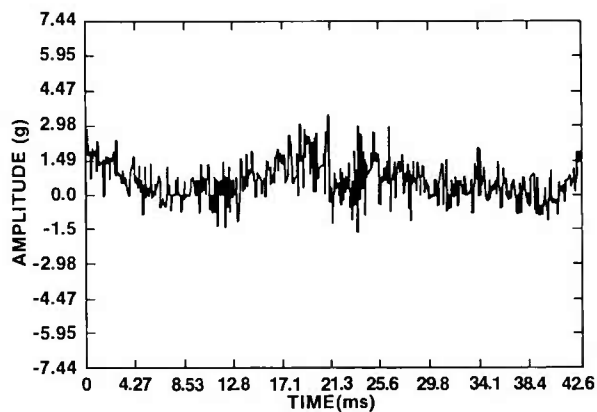
Figure IV-11. Case 2, No. 1: specified and synthesized transients--
PATRIOT fuze environment at launch (station 153, radial).



(a) specified half-sine pulse

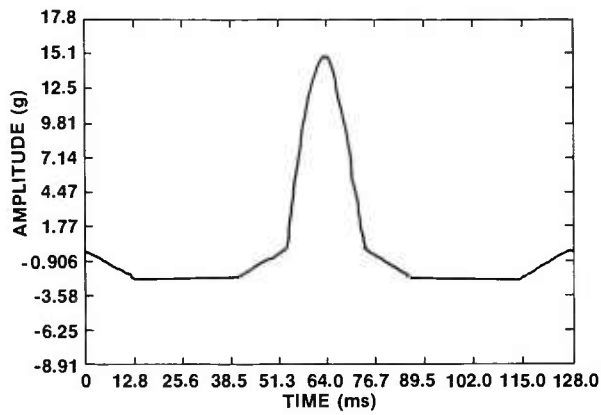


(b) synthesized half-sine pulse

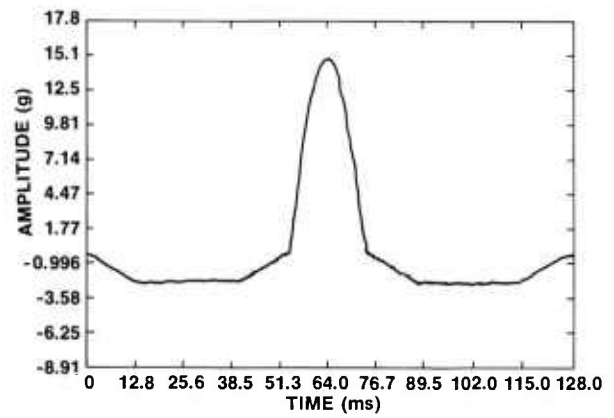


(c) error between specified and synthesized pulse

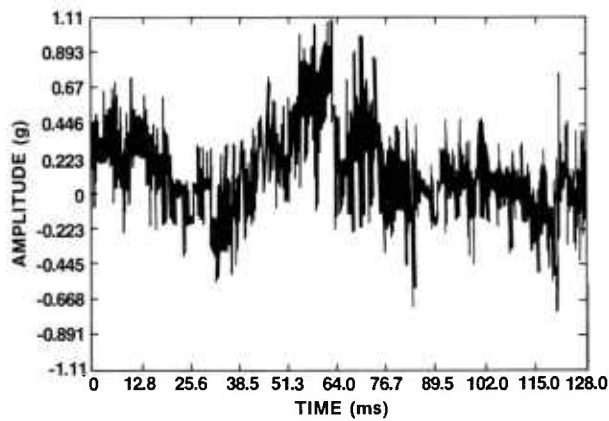
Figure IV-12. Specified half-sine pulse: 100 g, 6 ms, 3000 Hz, 128 lines (shown at quarter level).



(a) specified half-sine pulse

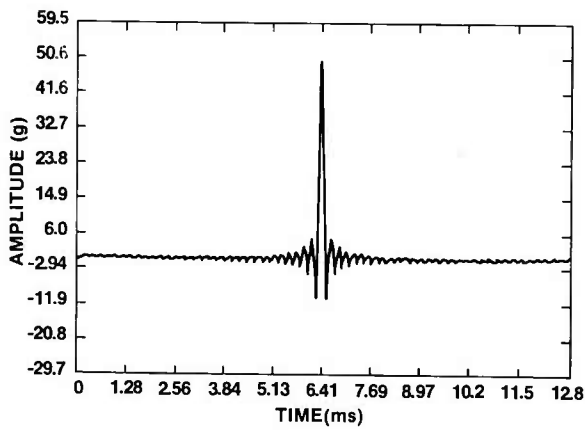


(b) synthesized half-sine pulse



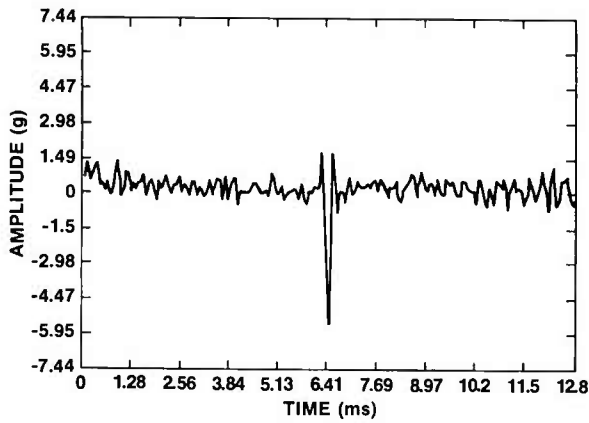
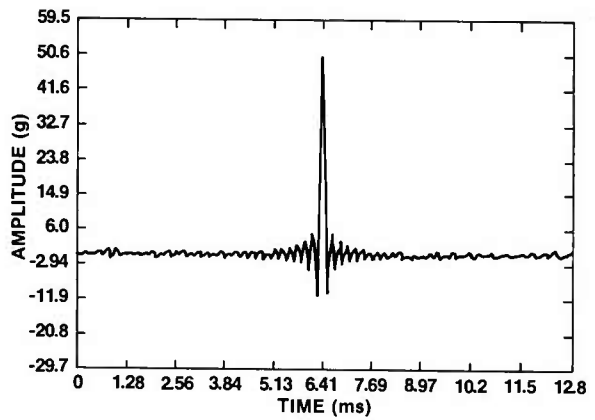
(c) error between specified and synthesized pulse

Figure IV-13. Specified half-sine pulse: 15 g, 20 ms, 2000 Hz, 256 lines.



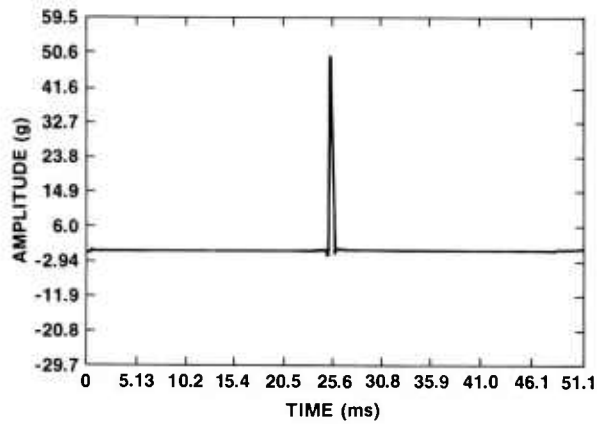
(a) specified half-sine pulse

(b) synthesized half-sine pulse



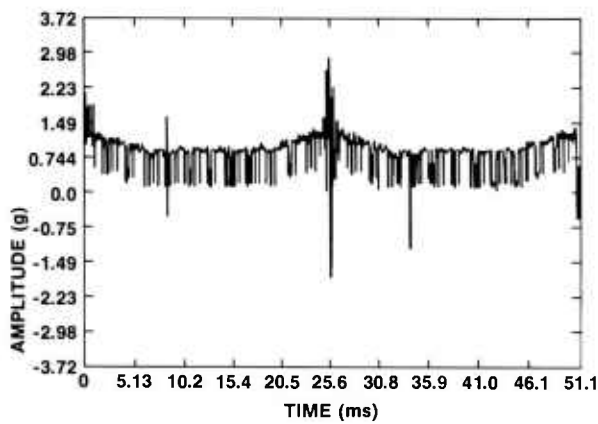
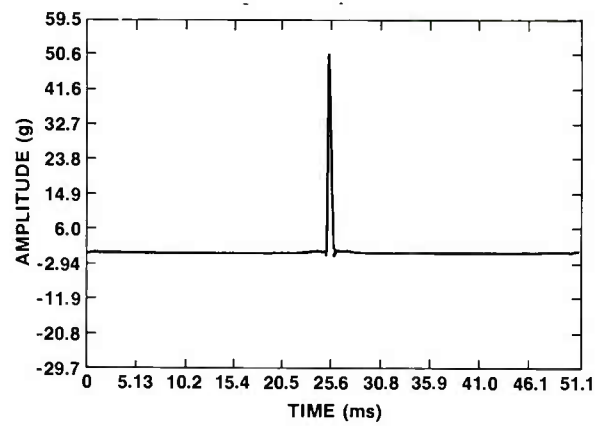
(c) error between specified and synthesized pulse

Figure IV-14. Specified half-sine pulse: 50 g, 6 ms, 5000 Hz, 64 lines.



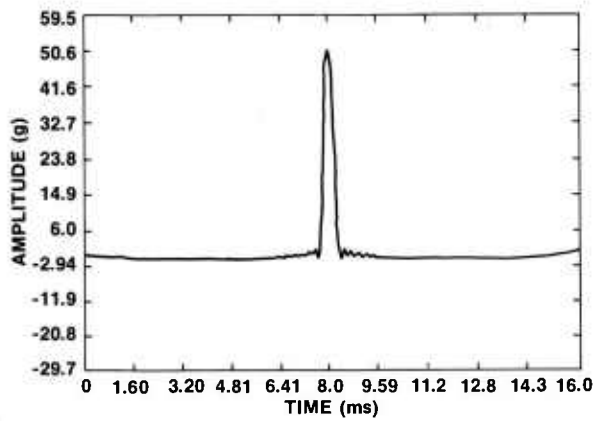
(a) specified half-sine pulse
(additional case)

(b) synthesized half-sine pulse



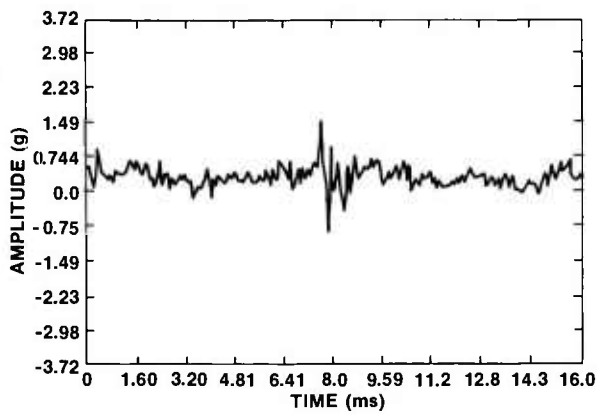
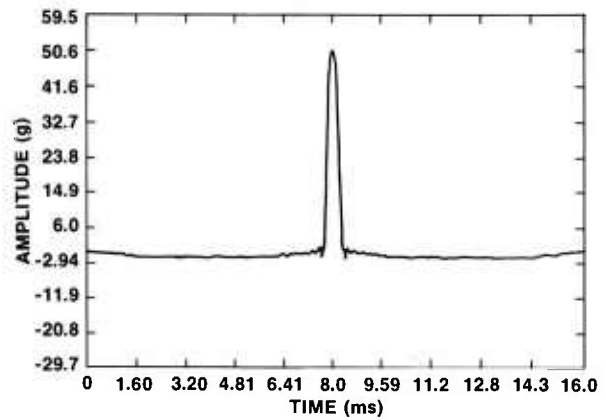
(c) error between specified and
synthesized pulses

Figure IV-15. Specified half-sine pulse: 50 g, 5 ms, 5000 Hz, 256 lines.



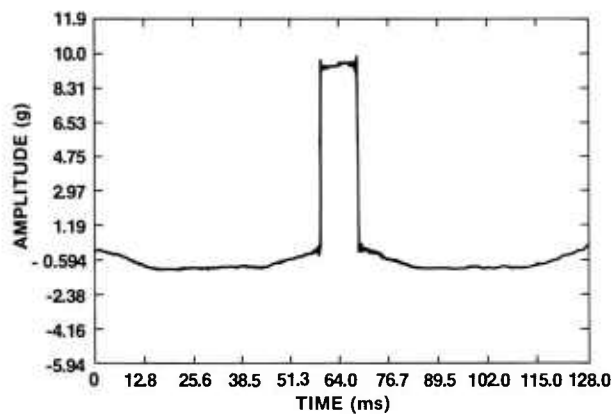
(a) specified half-sine pulse (additional case)

(b) synthesized half-sine pulse

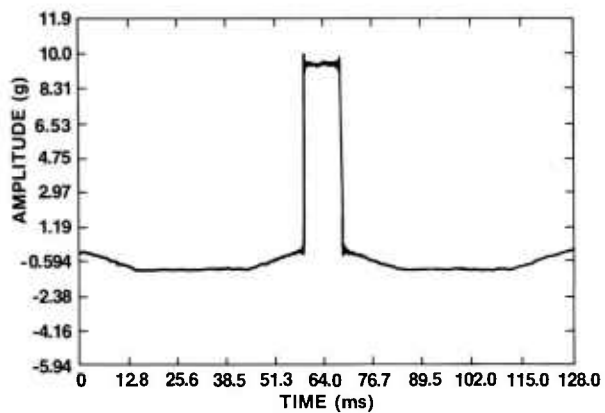


(c) error between specified and synthesized pulses

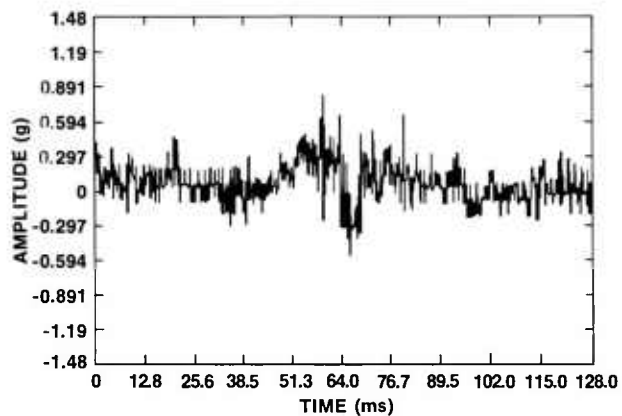
Figure IV-16. Specified half-sine pulse: 50 g, 6 ms, 4000 Hz, 64 lines.



(a) specified square pulse

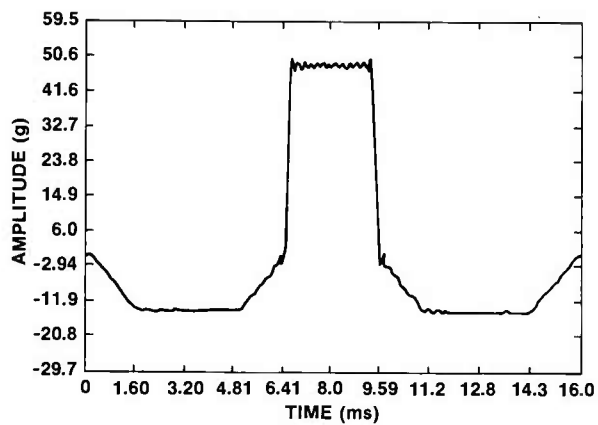


(b) synthesized square pulse

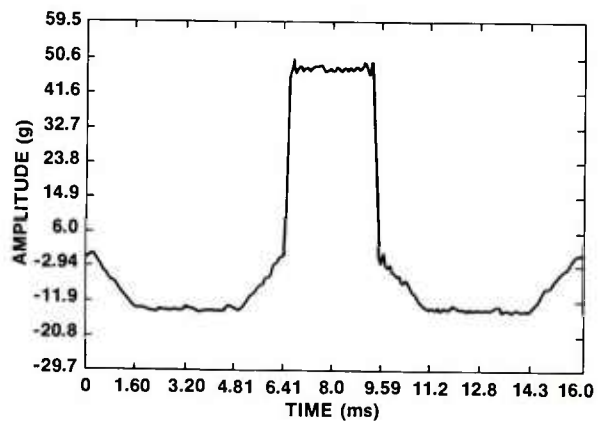


(c) error between specified and synthesized pulses

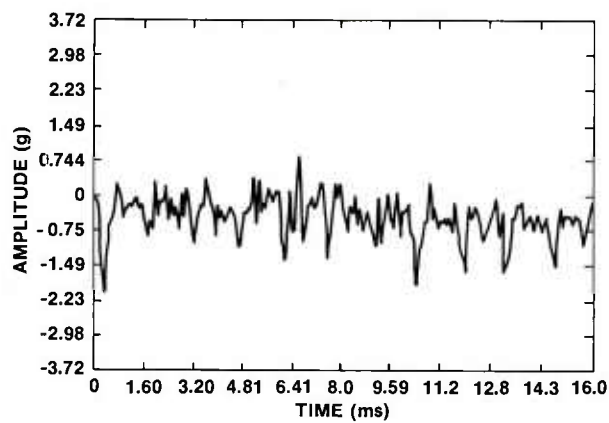
Figure IV-17. Specified square pulse: 10 g, 10 ms, 2000 Hz, 256 lines.



(a) specified square pulse

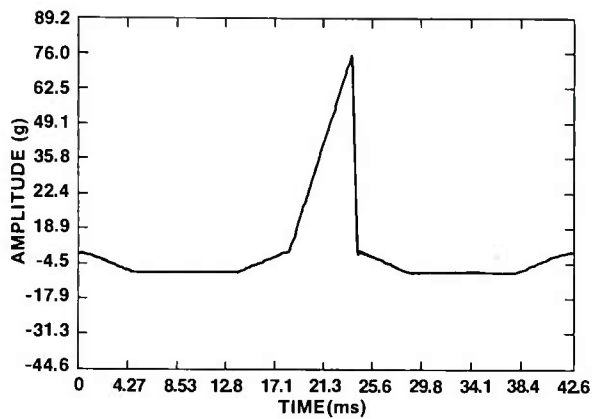


(b) synthesized square pulse



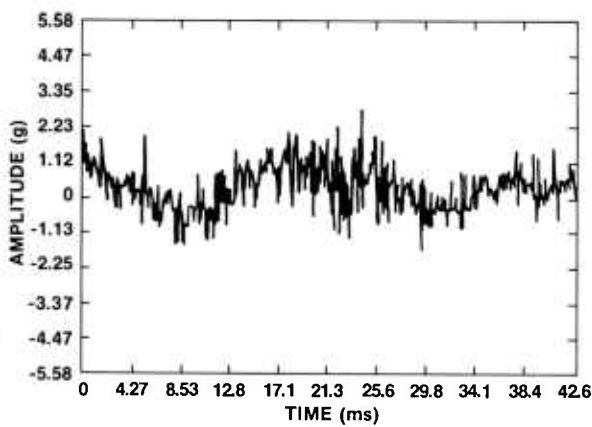
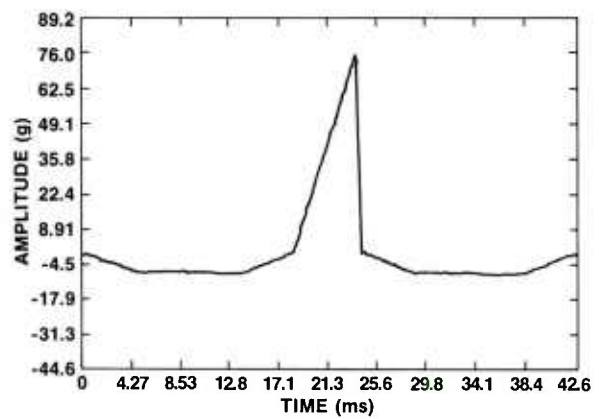
(c) error between specified and synthesized pulses

Figure IV-18. Specified square pulse: 50 g, 3 ms, 4000 Hz, 64 lines.



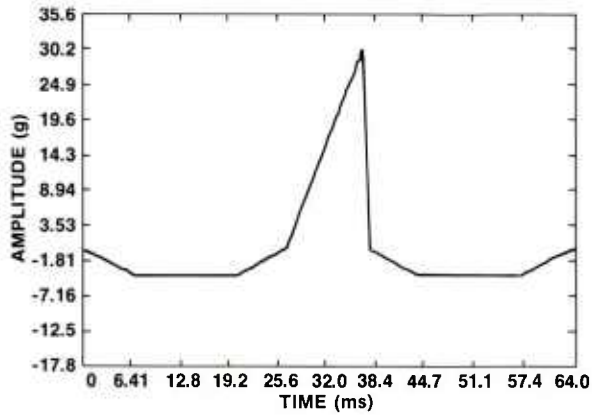
(a) specified terminal peak sawtooth pulse

(b) synthesized terminal peak sawtooth pulse



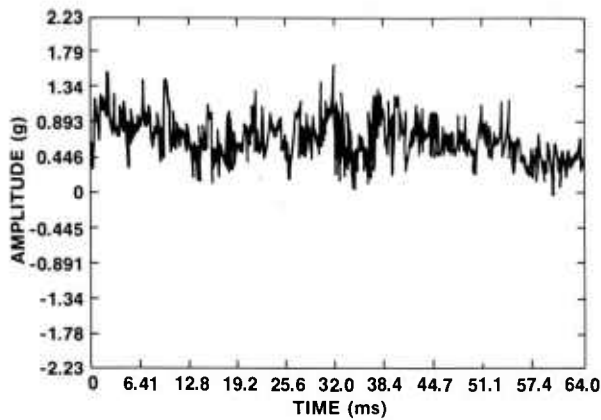
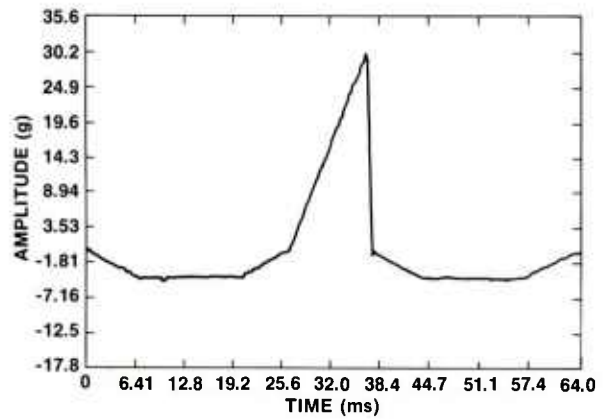
(c) error between specified and synthesized pulses

Figure IV-19. Specified terminal peak sawtooth pulse: 75 g, 6 ms, 3000 Hz, 128 lines.



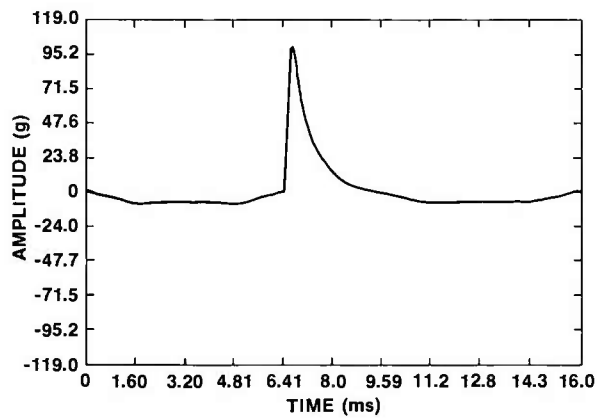
(a) specified terminal
peak sawtooth pulse

(b) synthesized terminal peak
sawtooth pulse



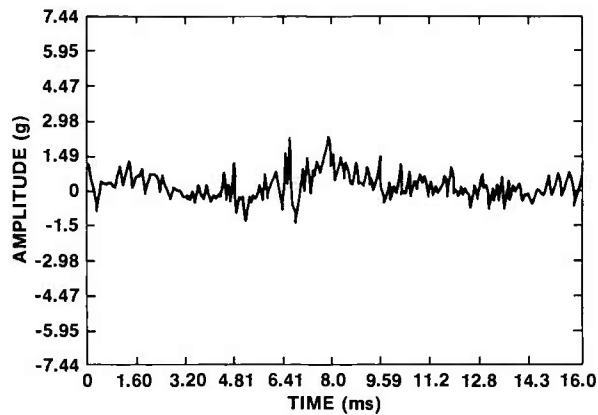
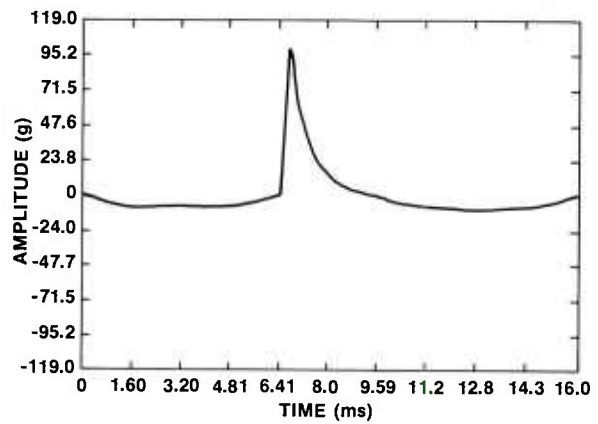
(c) error between specified and
synthesized pulses

Figure IV-20. Specified terminal peak sawtooth pulse: 30 g, 11 ms, 2000 Hz, 128 lines.



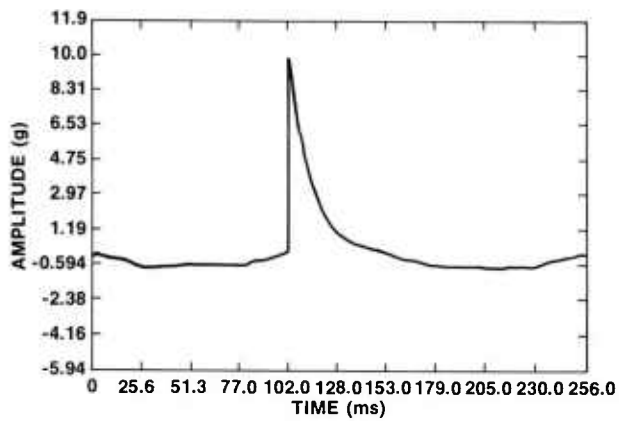
(a) specified exponential decay pulse

(b) synthesized exponential decay pulse



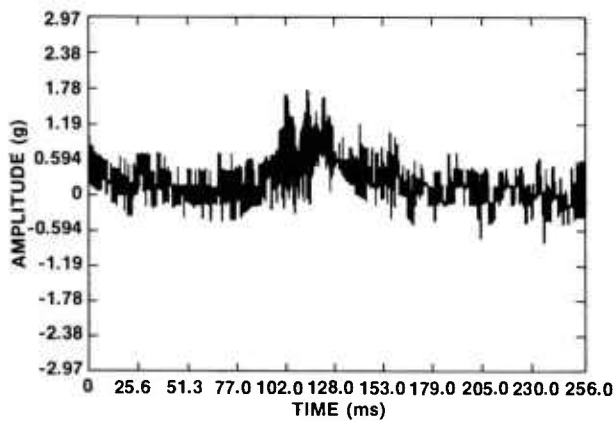
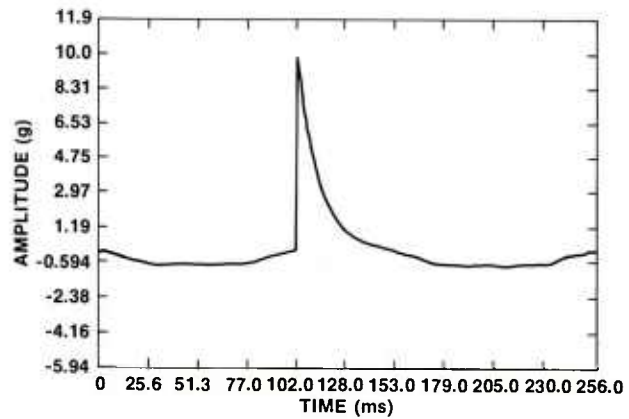
(c) error between specified and synthesized pulses

Figure IV-21. Specified exponential decay pulse: 100 g, 3 ms, 4000 Hz, 54 lines.



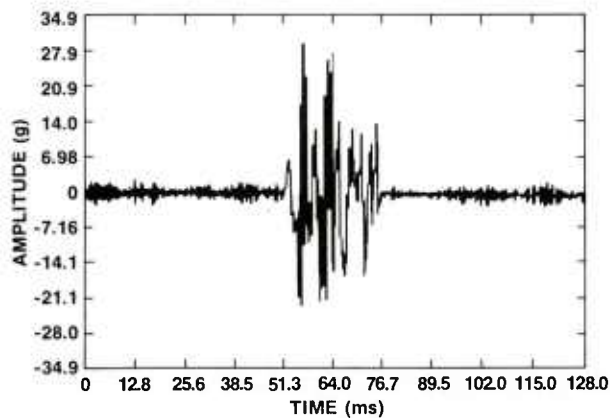
(a) specified exponential decay pulse

(b) synthesized exponential decay pulse



(c) error between specified and synthesized pulses

Figure IV-22. Specified exponential decay pulse: 10 g, 50 ms, 2000 Hz, 512 lines.



(a) synthesized transient
pulse: 25 ms, 55 points,
4000 Hz, 512 lines

(b) error between specified and
synthesized transients

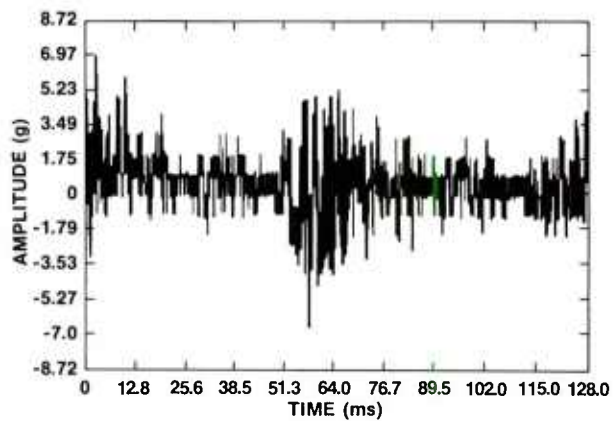


Figure IV-23. Case 1, No. 1: specified transient--PATRIOT
fuze environment at launch (station 153, longitudinal).

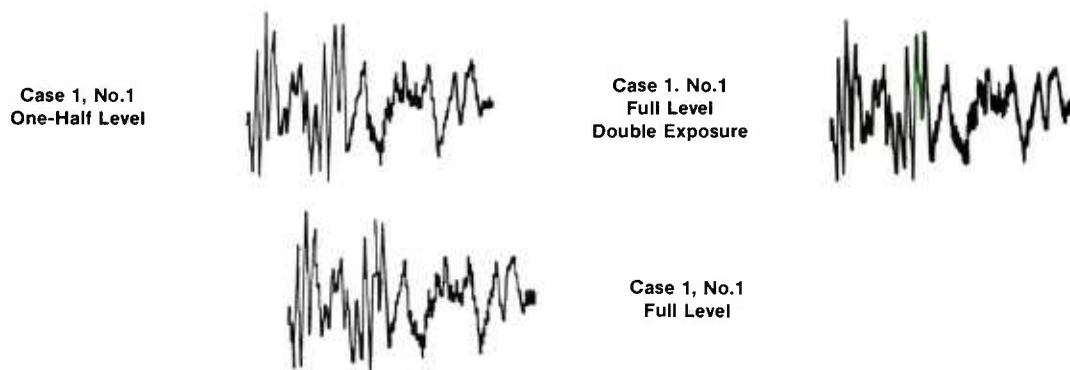


Figure IV-24. Case 1, No. 1: single and double exposures of the
synthesized pulse as displayed on oscilloscope screen.

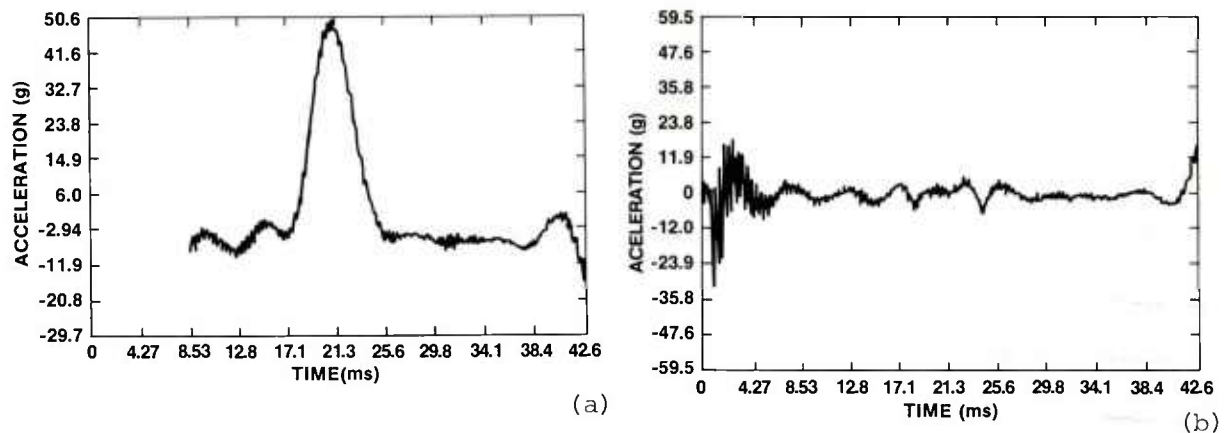


Figure IV-25. Synthesized half-sine pulse (half level): (a) 50 g, 6 ms, 3000 Hz, 128 lines, (b) error between specified and synthesized pulses.

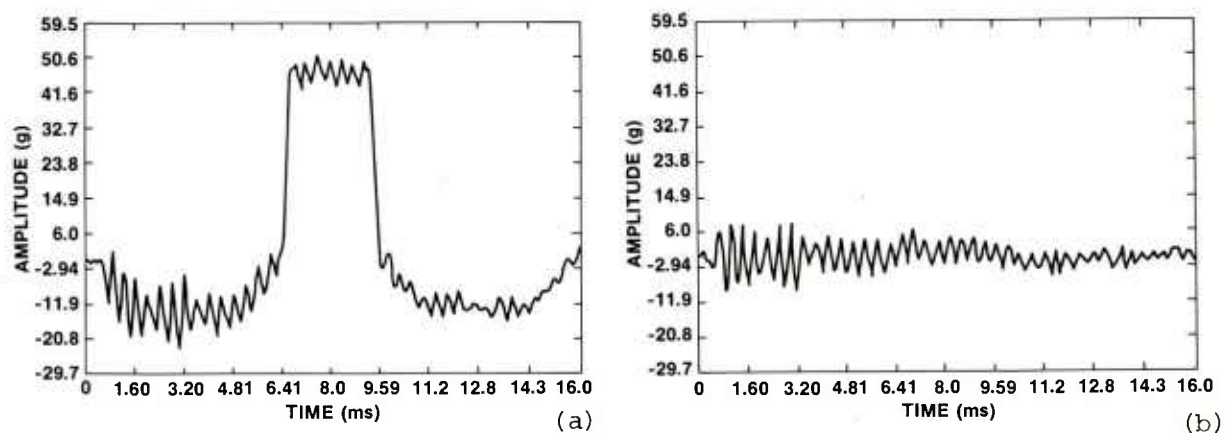
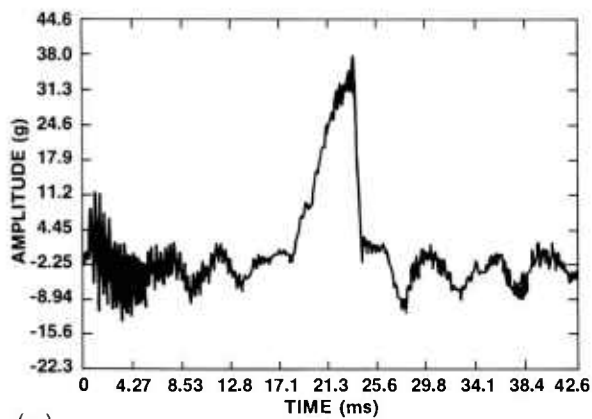
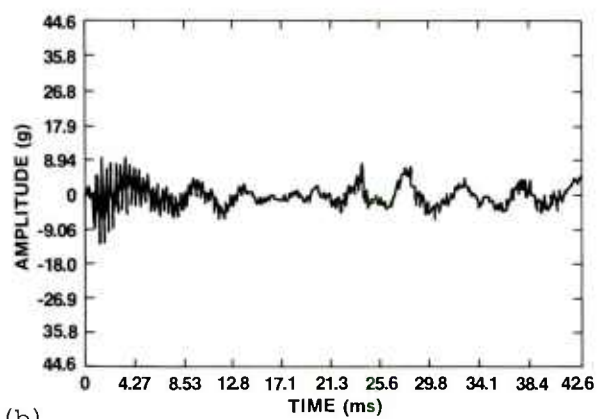


Figure IV-26. Synthesized square pulse: (a) 50 g; 32 ms, 4000 Hz, 64 lines, (b) error between specified and synthesized pulses.

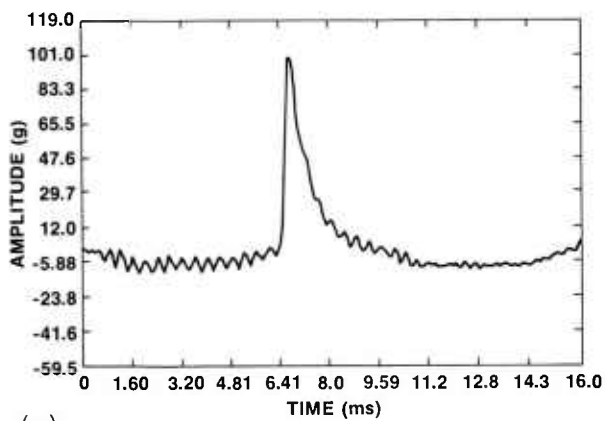


(a)

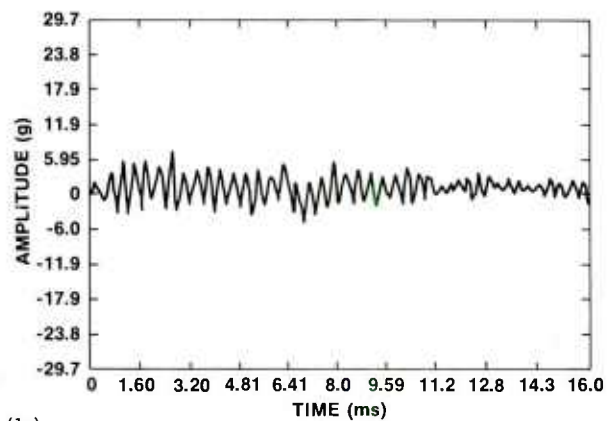


(b)

Figure IV-27. Synthesized terminal peak sawtooth pulse (half level):
(a) 38 g, 5 ms, 3000 Hz, 128 lines, (b) error between specified and synthesized pulses.



(a)



(b)

Figure IV-28. Synthesized exponential decay pulse: (a) 100 g, 3 ms, 4000 Hz, 64 lines; (b) error between specified and synthesized pulse.

APPENDIX A.--GENERAL SPECIFICATIONS FOR SOFTWARE

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The following appendix provides the specifications for software to perform transient waveform control and testing on Digital Control Test System T5021 (Harry Diamond Laboratories/Gilmore Industries).

A-1. GENERAL DESCRIPTION AND REQUIREMENTS

A-1.1 Description

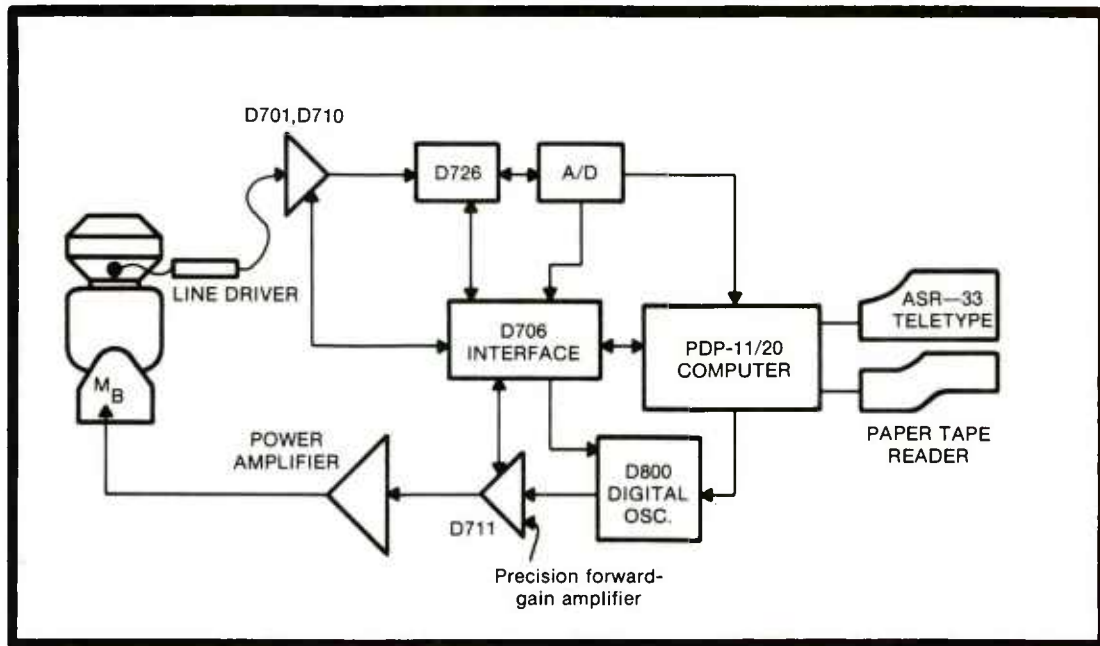
These specifications describe the software required for shock-transient waveform control testing in accordance with sections A-2 to A-11. Testing shall be performed on the existing Harry Diamond Laboratories (HDL) digital control sine/random test system model T5021 manufactured by Gilmore Industries. A block diagram of the test system is presented in figure A-1. Test specifications for the system are shown in table A-1. The T5021 system consists of the sine (T5001) and random (T5070) test systems. The entire test system, including test operations, shall be controlled by software (programs, instructions, or algorithms) that may be loaded into the digital processor/controller via a paper-tape reader of a teletype terminal.

The test method known as transient waveform control (TWC) permits control of electrodynamic vibration generators by an on-line digital computer to produce specific acceleration-time transient waveforms, be it a simple pulse (such as half-sine) or a complex waveform (such as the pulses resulting from pyrotechnic explosions, missile launches, etc.). The required transient can be read directly into the computer from analog magnetic tapes, or can be specified mathematically using such techniques as n-order polynomials, geometric definitions, or x-y entries of the acceleration-time data. The generated waveform must be reproduced within a specified statistical error calculated in the time domain.

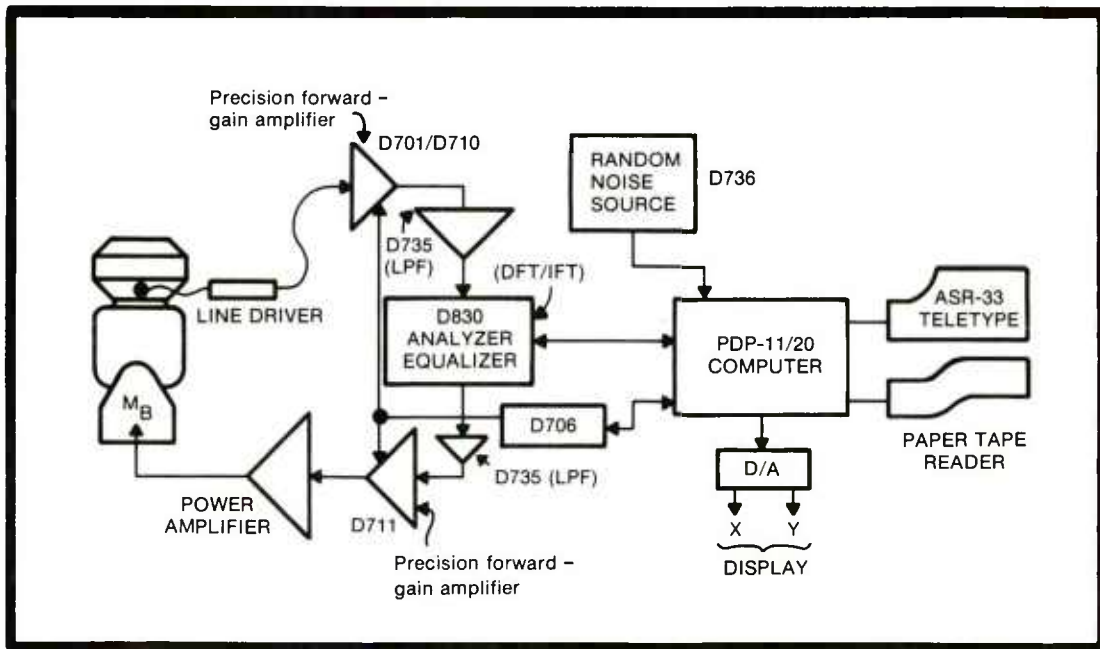
A-1.2 Operations

The operator must be able to define test parameters by answering simple conversational questions which are oriented to the test pattern. The operator can perform other controls via the keyboard using simple mnemonics. The system shall be oriented toward a laboratory technician who has no familiarity with digital programs or techniques. All operator entries and test information shall be printed on the teletypewriter for a permanent test record. In preparing a test program, the user shall have the use of a fully developed reentrant capability permitting immediate adjustment of previously defined data, without the user either going back to the beginning of the program or interfering in any way with other data already entered.

APPENDIX A



(a) SINE CONTROL



(b) RANDOM CONTROL Basic T5020 system.

Figure A-1. Basic T5020 system: (a) sine control, (b) random control.

TABLE A-1. GENERAL EQUIPMENT PERFORMANCE SPECIFICATIONS--T5021 TEST SYSTEM

GENERAL

System Input

Number of channels: 1 D701/D710 standard, multiple channel option available
 Input signal: Piezoelectric accelerometer and force transducers
 Sensitivity range: 1 to 100 mV/g unit or pC/g
 Conditioning mode: Zero drive voltage or charge
 Input signal voltage range: 6 μ V to 5 V pk, 1×10^{-3} g to 500 g at 10 mV/g
 Range steps: Binary 1, 4, 16, 64, 256, 1024
 Sensitivity set: Program control to 1 percent of point

System Control

Command input: Teletype (TTY) model ASR-33 (ASR-35 option available)
 Command format: Papertape-2-pass conversational papertape (disc or magnetic tape optional)
 Control mode: Automatic and manual
 Manual Mode: TTY access through four-letter code
 Test duration: Operator selected in setup
 Control tolerance: Operator specified alarm and abort limits (0.5 dB min.)

RANDOM SYSTEM MODEL T5020

Frequency range: 0 to F Hz, where F is operator selected to be any value between 500 Hz and 5 kHz
 Filter resolution: Operator selected 128 lines, 256 lines, or 512 lines (e.g., 128 lines - 15.6 bandwidth at 2000 Hz).
 Correction speed: equalized within 1 s
 Dynamic range: Digital process of 96 dB control/programming better than 60 dB
 Control accuracy: Better than 1.5 dB
 Analyzer accuracy: Better than 0.5 dB (400 degrees of freedom)
 System noise: Better than -70 dB below full scale
 Full-scale spectrum range: 1×10 g/Hz to 10 g²/Hz with input normalized to 10 mV/g
 System documentation: Teleprinter documents PSD versus frequency at completion of tests
 System monitoring: Digital-to-analog converters supplied to drive a standard analog X, Y plotter or oscilloscope.

Off-Line Analysis

Frequency range: 0 to F Hz, where F is operator selected for any value to 10 kHz
 Sample rates: 0 to 70 kHz
 Spectral lines: 64 to 1024 operator selected in 2-in. steps
 Dynamic range: 96 dB overall (digital processor)
 Input range: 6 μ V to 5 V peak
 Display: See system monitoring
 Analysis modes: Power spectrum, fourier (CO-QUAD) spectrum, other analysis modes optional
 Anti-aliasing filters: 10-pole Butterworth filter in D701.

SINE SYSTEM MODEL T5001

Frequency

Range: 0.5 Hz to 10 kHz
 Accuracy: 10 parts per million
 Resolution: 0.1 percent of point

Sweep

Rate: 0.01 to 6.0 octaves/min
 Mode: Log (linear optional)

Compressor

Mode: Automatic (computer optimized)
 Speed: Up to 2000 dB/s

Accuracy: 20 dB compressed to 0.4 dB
 40 dB compressed to 0.8 dB

System dynamic range: 60 dB

Oscillator distortion: Less than 0.5 percent

Output

Sine/cosine

DC proportional to frequency

Programming: Up to 10 levels any combination of displacement, velocity, acceleration.

Test documentation: List 3 points per octave frequency and amplitude automatically. Operator may request additional points.

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A-1.3 Control Computer

The central processing unit (CPU) is a PDP 11/20 digital minicomputer manufactured by the Digital Equipment Corporation. The present core size is 16K-words, expandable to 28K-words without the need for data management routines. Unless otherwise specified, additional hardware required to accommodate or operate the software shall be supplied with the software package(s) as part of this contract.

A-1.4 Delivery Requirements

Unless otherwise specified, the software package shall be furnished to HDL within 100 calendar days following award of contract. Acceptance testing shall be in accordance with section A-10.

A-2. TRANSIENT WAVEFORM CONTROL TESTING/PROCEDURE

A-2.1 Method

The TWC method is a test technique by which modern digital computers and Fast-Fourier-Transform (FFT) processors are used "on line" to control specified transient time histories of motion on vibration generators. The theory behind the TWC concept is fundamental linear systems theory as presented below.

A-2.2 Requirements

TWC testing shall be performed in accordance with the procedure outlined in section A-2.3. A block diagram of the TWC process is presented in figure A-1. Methods for describing and programming the required transient(s) shall be in accordance with section A-4.

A-2.3 Procedure

TWC testing shall be performed according to the following procedure.

(a) Read in the digital description of the required transient waveform $f_r(t)$, $f_r(t) = 0$, $t \leq 0$.

(b) The shaker system input calibration pulse $f_i(t)$ is selected so that the frequency range of its Fourier transform extends over the entire operating range of the system (see sect. A-4.4.1 and A-4.4.2 for frequency range).*

*The program shall automatically compute the time duration of the calibration pulse based on operator-specified frequency range.

This pulse shall be of the exponential decay type as described in equation (A-1) below, In addition, all computations and data required to perform TWC shall be retained in memory for the duration of the test for subsequent dump on paper tape.

$$\begin{aligned} f_i(t) &= Ae^{-at} \neq 0, \quad t \geq 0, \\ &= 0, \quad t \leq 0, \end{aligned} \quad (A-1)$$

where

$A = f_i(0)$, a = time constant, t = time, and $f_i(t)$ = voltage representation of input calibration pulse.

(c) Calculate $F_i(w)$, the discrete Fourier Transform (DFT) of $f_i(t)$.

$$F_i(w) = \text{DFT}[f_i(t)] \quad (A-2)$$

Whenever a DFT is required, it shall be defined in accordance with section A-2.4.*

(d) Calculate $F_o(w)$, the DFT of the response $f_o(t)$ of the system/shaker/specimen to the calibration pulse $f_i(t)$.

$$F_o(w) = \text{DFT}[f_o(t)] \quad (A-3)$$

(e) Form the test system/shaker/specimen transfer function $H_s(w)$, where w denotes frequency.

$$H_s(w) = F_o(w)/F_i(w) \quad (A-4)$$

(f) Compute $F_r(w)$, the DFT of the required transient $f_r(t)$.

$$F_r(w) = \text{DFT}[f_r(t)] \quad (A-5)$$

*Refer to the literature for an FFT algorithm.

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(g) Divide equation (A-5) by the $H_s(w)$ to form $F_s(w)$ the DFT of the required transient, and system/shaker/specimen transfer function.

$$F_s(w) = F_r(w)/H_s(w) \quad . \quad (A-6)$$

(h) Perform the Inverse Fourier Transform (IFT) of $F_s(w)$ to generate the digital time-dependent voltage $E_r(t)$ to drive the shaker in accordance with section A-2.2 above.

$$E_r(t) = \text{IFT}[F_s(w)] \quad . \quad (A-7)$$

Whenever the IFT is required, it shall be defined in accordance with section A-2.4.*

(i) Transmit the digital representation of $E_r(t)$ to the digital-to-analog (D/A) converter to obtain an analog representation of this quantity. This voltage is to be fed into the power amplifier and subsequently to the shaker.

(j) The overall transfer function $H_s(w)$ shall be computed iteratively until the generated transient complies with error requirements listed in section A-3 (the control software for the HDL system contains error convergence subroutines not described in this section).

(k) The peak level of the calibration pulse shall not exceed one-third the peak level of the specified transient.

A-2.4 FFT

The FFT is a discrete Fourier Transform based upon the following reciprocal equations of the Fourier Transform:

$$A(n) = \sum_{k=0}^{N-1} x(k)e^{-j2\pi nk/N} \quad , \quad n = 0, 1, 2, \dots, N-1 \quad , \quad (A-8)$$

where $A(n)$ is the discrete Fourier Transform of $x(k)$; the IFT of $A(n)$ is given by

$$x(k) = \sum_{n=0}^{N-1} A(n)e^{j2\pi nk/N} \quad , \quad k = 0, 1, 2, \dots, N-1 \quad . \quad (A-9)$$

*Refer to the literature for an IFFT algorithm.

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The quantities $A(n)$ and $x(k)$ represent number sets only. N equals the number of data values in each set. The summation counters are n and k . In this form, they are not restricted to a time-frequency-domain relationship.

Equations (A-8) and (A-9) are used to compute discrete Fourier Transforms in units of time and frequency by inclusion of the sampling increments, Δt , Δf , and use of the following theorem.

If $x(t)$ (a continuous time function for $-\infty < t < \infty$) and $A(f)$ (a continuous frequency function for $-\infty < f < \infty$) are a Fourier integral transform pair,

$$x(t) \longleftrightarrow A(f) ,$$

then

$$x_p(k\Delta t), k = 0, 1, 2, \dots N - 1$$

and

$$A_p(n\Delta f), n = 0, 1, 2, \dots N - 1$$

are a discrete Fourier Transform pair, where

$$\Delta f = \frac{1}{N\Delta t} = \frac{1}{T} = \frac{\Delta W}{2\pi} , \quad (A-10)$$

and

p = particular sample signal of duration T ,
 N = total number of samples (time data points),
 Δt = time-sampling interval,
 T = time duration of sample signal ($T = N\Delta t$),
 Δf = frequency sampling interval (Hz),
 ΔW = frequency sampling interval (rad/s).

The resulting transform pair are

$$A_p(n\Delta f) = \Delta t \left[\sum_{k=0}^{N-1} x_p(k\Delta t) e^{-j2\pi nk/N} \right] \quad (A-11)$$

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and

$$x_p(k\Delta t) = \Delta f \sum_{n=0}^{N-1} A_p(n\Delta f) e^{j2\pi nk/N} , \quad (A-12)$$

where

$$\begin{aligned} A_p(n\Delta f) &= n^{\text{th}} \text{ complex frequency sample} \\ x_p(k\Delta t) &= k^{\text{th}} \text{ time sample} \\ N &= \text{total number of samples} \\ j &= \sqrt{-1} . \end{aligned}$$

A-3. ERROR ANALYSIS FOR TWC TESTING

The following requirement applies to complex transient waveforms as defined in section A-4.1 (e). The error between the generated transient and the specified transient shall be computed in the time domain. This error, designated the quantity E in equation (A-18), shall be limited to 10 percent, unless otherwise specified. The evaluation of the error shall be as follows.

Let $x = x(t)$ = specified transient-waveform time domain,
 $y = y(t)$ = generated transient-waveform time domain,
 $e = e(t)$ = error signal in time domain, and
 $i = 1, 2, 3, \dots N$ = index of discrete data points in time domain.

The i^{th} error can be expressed as

$$e_i = x_i - y_i . \quad (A-13)$$

Let the statistical mean of the specified transient in the time domain be denoted by

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i , \quad (A-14)$$

and the mean resulting error, be denoted by

$$\bar{e} = \frac{1}{N} \sum_{i=1}^N e_i . \quad (A-15)$$

The variance of the discrete specified data points (i.e., transient waveform) with respect to the mean is given by σ_x^2 :

$$\sigma_x^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2, \quad (A-16)$$

and the corresponding variance for the discrete errors with respect to the mean error is given by σ_e^2 :

$$\sigma_e^2 = \frac{1}{N} \sum_{i=1}^N (e_i - \bar{e})^2. \quad (A-17)$$

Thus, the measure of the overall variance error for the sample, σ_e , can be expressed as follows in units of percent of the variance of the discrete specified data, σ_x .

$$E = \frac{\sigma_e^2}{\sigma_x^2} \times 100. \quad (A-18)$$

This requirement applies to all simple pulses (except complex) as indicated in (a), (b), (c), and (d) of section A-4.1.

The error between the generated and the specified transient shall be in accordance with the requirements set forth in MIL-STD-810B and subsequent revisions as of 31 January 1975. (The percent error allowable for the half-sine pulse shall apply to the exponential decay and square pulses.)

A-4. TRANSIENT WAVEFORM DEFINITION AND PERFORMANCE REQUIREMENTS

Using the appropriate software routines the T5021 test system shall be able to generate the transient waveforms defined in section A-4.1 within the error requirement of section A-3. The specified transient waveform shall be generated within the limitations listed in the following sections.

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A-4.1 Transient Waveforms

The types of transient waveforms are listed below.

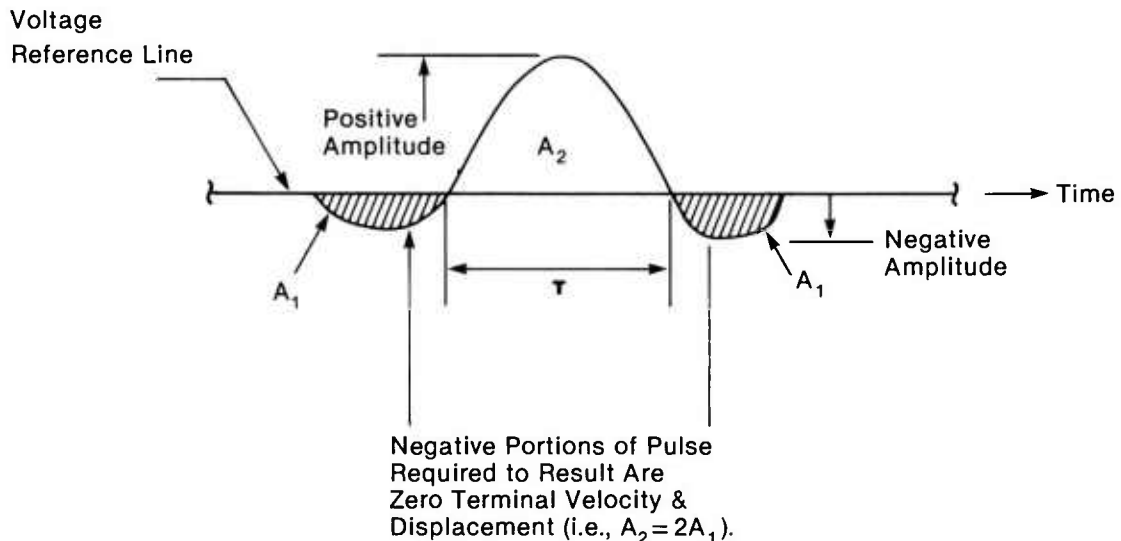
- (a) Half-sine
- (b) Terminal peak sawtooth
- (c) Square (trapezoidal)
- (d) Exponential decay
- (e) Complex (periodic and nonperiodic)

A-4.2 Time Duration

The duration of simple pulses and complex transients shall be as follows.

(a) Simple Pulses (per sect. A-4.1, a, b, c, and d)

1. The time duration shall be within the range set for τ , where $0.5 \text{ ms} \leq \tau \leq 75.0 \text{ ms}$. As indicated in the sketch below the quantity τ designates the total pulse time only.



2. Unless otherwise specified the negative amplitude of the pulse shall not exceed 10 percent of the peak. However, in the override mode the user shall have the capability to specify a negative amplitude in excess of 10 percent of the peak (the distribution of the two negative portions of the pulse shall be symmetrical with respect to the center of the pulse).

(b) Complex Transients (per sect. A-4.1, e and f)

1. The time duration for the transient waveform shall be based on the following relationships:

$$T = \left(\frac{NS}{SR} \right) ,$$

where

T = time duration for transient (s),
 NS = number of samples in the time domain,*
 SR = sample rate (samples/s) $\geq 3 F_{\max}$,
 F_{\max} = maximum test frequency (i.e., upper limit of test frequency) and also the Nyquist cutoff frequency.

2. Additional time required to result in zero terminal velocity and displacement shall not be included in the quantity T expressed in section A-4.2 (b).

A-4.3 Amplitude and Frequency Ranges

The amplitude range should be: 0.1 to 120 g, except as modified by the following T5021 system/C90 shaker limitations.

- (a) Velocity: 70 ips
- (b) Displacement: 0.75 in. d.a.
- (c) Force: 7000 lb

The frequency range should be: 5 to 5000 Hz.

The operator shall have the capability of defining the system frequency range from 5 to 5000 Hz. The system shall have basic frequency ranges from 5 to 500 Hz, 5 to 1000 Hz, 5 to 2000 Hz, 5 to 3000 Hz, 5 to 4000 Hz, and 5 to 5000 Hz.

The operator shall have the capability of specifying any desired analysis bandwidth within any of the basic frequency ranges.

A-4.4 Other Requirements

The operator shall be able to select the analysis resolution for the FFT computations as follows.

**N real-valued data points in the time domain will yield N/2 complex-valued spectral lines in the frequency domain. Thus, a 1024-point FFT will yield 512 spectral lines from 0 to F_{\max} frequency.*

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- (a) 64-line resolution (96 frequency samples),
- (b) 128-line resolution (192 frequency samples),
- (c) 256-line resolution (384 frequency samples),
- (d) 512-line resolution (768 frequency samples), and
- (e) 1024-line resolution (1536 frequency samples).

The total time to generate the required transient waveform shall not exceed 1.0 min from the time the transient has been specified (i.e., programmed) to the control computer.

Prior to testing, the program shall verify that the rms level of the system's random noise is at least 25 dB below the rms level for the specified transient waveform (this information is required to assist the operator in selecting the accelerometer with the appropriate sensitivity for the indicated signal-to-noise ratio).

A-4.5 Optional Characteristics

The program shall be able to compute and list the following parameters for simple (classical) pulses given in table A-2.

TABLE A-2. PARAMETERS FOR SIMPLE (CLASSICAL) PULSES

Quantity	Generated Transient	Specified Transient	Pulse
ΔV	Y	Y	(a)
V_{\max}	Y	Y	(a)
ΔS	Y	Y	(a)
S_{\max}	Y	Y	(a)

^aMust conform to requirements a, b, c, and d of section A-4.1.

In the preceding table, A-2,

Y = yes,

$$\Delta V = \text{total velocity change} = \sum_{i=1}^N \ddot{x}(t)_i \Delta t_i ,$$

V_{\max} = maximum velocity (absolute),

$$\Delta S = \text{total displacement} = \sum_{i=1}^N \dot{x}(t)_i \Delta t_i ,$$

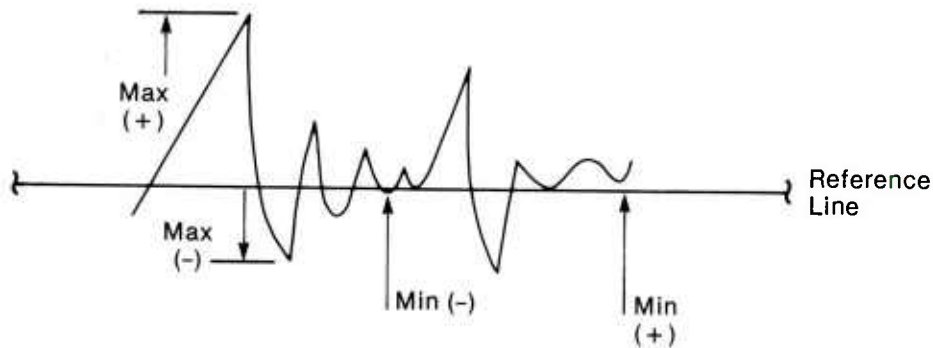
S_{\max} = maximum displacement (absolute),

$\ddot{x}(t)$ = transient acceleration,

$\dot{x}(t)$ = transient velocity, and

$i = 1, \dots, N$ = index for digital samples.

For complex transients (per sect. A-4.1 e and f), the maximum/minimum velocity and displacements shall be determined as follows (both positive and negative quantities are required).



A-5. SYSTEM CONTROL FOR TWC TESTING

The equalizer system shall be based on the use of the separate closed-loop servomechanism control for each individual spectral line. The closed-loop control shall be continuous and shall respond as fast as permitted by servomechanism loop stability criteria for the existing T5021 system hardware.

The operate program shall be operable in two modes, as decided by the user. In the automatic mode the program, once prepared and certified, shall be unchangeable so that the integrity of the vibration test shall be preserved, immune from any possible extraneous operator interference. In this regard, no control panel is to be permitted; also, no manual gain or other adjustment is to be permitted.

In the manual mode the program, once prepared, shall be capable of modification during the test phase. This second mode shall permit a sufficient level of reaction of operator-induced changes, to permit adjustments in control levels and frequencies needed to study the response of the test specimen.

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In both modes, the operator shall always have control over documentation requests, as well as a capability to initiate manual test abort functions.

The test system shall automatically run wideband TWC tests as previously defined by the operator in answer to conversational questions.

The operator shall be able to select a low-level equalization value. This level shall be used prior to attempting a quarter level of equalization.

The system shall be designed to proceed from low-level equalization to one-quarter level equalization, during which the criteria for equalization shall be tightened and test results of this level shall be printed out.

The control system shall be designed to proceed from the one-quarter level on operator command to either a one-half or full-level pulse. Single or multiple pulses may be selected by the operator.

A-6. METHODS OF SPECIFYING THE REQUIRED TRANSIENT WAVEFORM

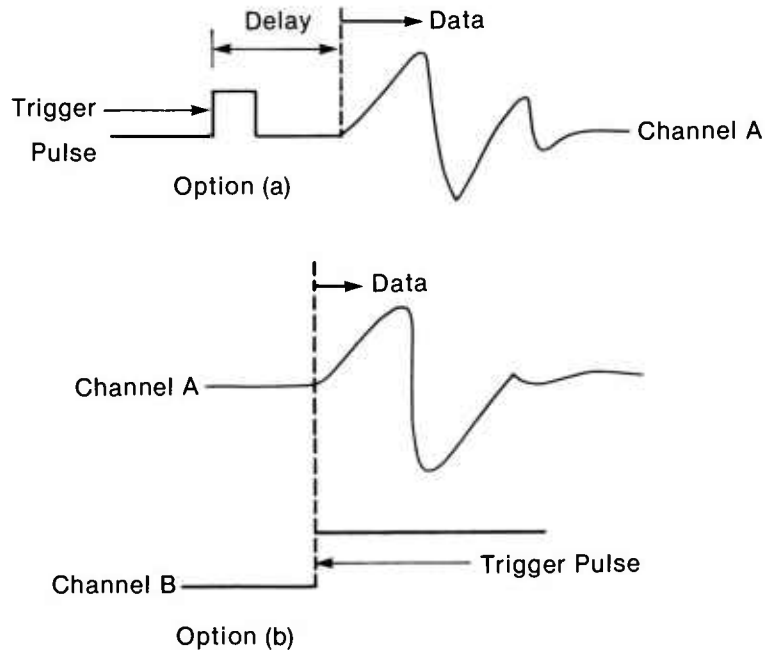
A-6.1 External Inputs

The T5021 test system shall accept external inputs (of the required transient waveform) from magnetic tapes or other voltage sources with a 1000-ohm or less output connector impedance. The input to the system shall be at the D701 module using the standard (microdot) port for the return signal or via a specially adapted connector. (The input port shall be consistent with the system technical specifications described in table A-1.) The software shall be so designed as to cause the test system to reproduce the input transient presented from external voltage sources upon the exciter head within its present mechanical and electrical limitations.

The program shall be capable of generating the standard 8-bit ASCII paper-tape punch of the externally specified transient such that this tape could be used repeatedly in testing without the need to rely on external data sources. This requirement shall hold for all forms of programming of the transient waveform.

The test system shall be capable of executing TWC testing using pre-punched data tapes as defined previously. The paper tape shall be entered via the existing paper-tape reader.

In order to initiate data read-in from an external analog voltage source, a trigger voltage pulse shall be provided by the test facility as follows:



Outputs from channels A and B shall be available for input into the D701 module or equivalent unit. The least costly option shall be implemented by the contractor.

The software shall interactively indicate to the operator the optimum analysis bandwidth and spectral lines such that the input transient waveform data are not truncated due to limitations on the time frame.

The software shall have provisions to relate the playback speed of the input data to the original recording speed; in addition, provisions shall be made in the software to relate the time base of the original recording to the time base of the recorded event.

A-6.2 Internal Inputs

The following applies to internal input (i.e., operator programmed) transients using teletype keyboard commands.

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Definition of simple transients (see sect. A-4.1 excluding e and f) shall be accomplished using keyboard commands. The operator shall specify the transient type, amplitude, and duration, thereby completely defining the transient.

The operator shall have the capability to define any transient waveform by specifying sets of X-Y points corresponding to the acceleration-time domain. The total number of points shall be selected by the operator (this routine assumes linear interpolation between points). Using keyboard command the software shall allow the desired transient to be programmed in the form of a polynomial of up to the tenth order as follows.

$$f(t) = At^n + Bt^{n-1} + Ct^{n-2} + \dots Q_0, \quad (A-19)$$

where

$f(t)$ = desired transient waveform,
 $A, B, C, \dots Q$ = coefficients of best-fit n^{th} -order polynomials,
 t = time,

and

$$0 \leq n \leq 10 = \text{order of polynomial}.$$

The operator shall specify the coefficients, order of polynomial, and test time.

The software shall have the capability of generating $x(t)$, the sum of sinusoids, as follows.

$$x(t) = A_1 \sin(w_1 t + \phi_1) + A_2 \sin(w_2 t + \phi_2),$$

where

$A_{1,2}$ = specific amplitudes,
 $w_{1,2}$ = specific frequencies,

and

ϕ_1, ϕ_2 = specific phase angles relative to a reference.

Using keyboard commands, the operator shall specify to the system the amplitudes, frequencies, phase angles, and test times.

The system shall allow the desired transient to be entered in the form of a Fourier series representation as follows.

$$f(t) = Q_0 + \sum_{n=1}^N (A_n \cos n\omega t + B_n \sin n\omega t) \quad (A-20)$$

and

$$A_n = \frac{2}{T} \int_0^T f(t) \cos n\omega t \, dt ,$$

$$B_n = \frac{2}{T} \int_0^T f(t) \sin n\omega t \, dt ,$$

where $f(t)$ = desired transient waveform,

A_n, B_n = coefficient of Fourier series,

N = total number of data points,

T = period of transient, and

Q_0 = average value of $f(t)$.

The operator shall specify the required input to perform the computations.

A-6.3 Options (optional only for sect. A-6.3)

In lieu of the methods for specifying the various transient waveforms as outlined previously, the contractor shall provide programming capabilities such that the operator could apply the BASIC language to specify the input transient mathematically for any well-behaved continuous waveform, including complex pulses.* This option does not apply to the external input method.

*Per requirements of section A-4.

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A-7. DATA INPUT REQUIREMENTS TO EXECUTE TWC TESTING

The following information shall be supplied to the software (via keyboard commands) to perform TWC testing.

- a. Run identification, operator ID, and test data
- b. Test description
- c. Accelerometer sensitivity in mV/g
- d. Maximum g for the specified transient
- e. n level for test ($n = 1/8, 1/4, 1/2, 3/4, 1.0$, where 1.0 = full level)
- f. low/high alarm and abort limits (in decibels)
- g. Transient waveform description (half-sine, complex, etc.)
- h. Duration of transient (ms)
- i. Analysis bandwidth (optimum, per sect. A-6.1 in Hz)
- j. Number of spectral lines
- k. Method of programming of pulse (external, internal, x-y, etc.)
- l. Number of repetitive applications of the transient with a specified delay in between

A-8. DATA OUTPUT REQUIREMENTS FOLLOWING TWC TESTING

Following execution of the specified transient the following output shall be listed by the teletypewriter printer.

Teletypewriter Printer Output

- a. Test identification: D (= description)
- b. Test operator: D
- c. Test date: D
- d. Transient: D
- e. Duration: (ms) D
- f. Number of samples analyzed: D
- g. Attempt No.: D
- h. Analysis bandwidth: Hz
- i. Bandwidth: Hz
- j. No. of spectral lines: D
- k. Variance error (e): percent
- l. Standard deviation for error (σ_e): percent
- m. Standard deviation for transient (σ_x): percent
- n. Mean error (\bar{e}): percent
- o. Overall variance error (E): percent
- p. Mean generated transient (\bar{Y}): g's
- q. Mean specified transient (\bar{X}): g's

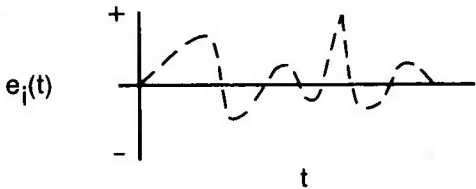
Optional Output

DV, V_{\max} , DS, S_{\max} as specified in section A-4.7.

Upon (Y/N) command the teletypewriter printer shall generate the following plot package on the T5021 system existing Hewlett Packard X-Y plotter (8.5- x 11-in. field).

$$e_i(t) = X_i(t) - Y_i(t)$$

where $e_i(t)$ is plotted versus t .



Upon operator command the teletypewriter printer shall list the following.

<u>N</u>	<u>RE(N)</u>	<u>IM(N)</u>	<u>RE(N+1)</u>	<u>IM(N+1)</u>
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

Entire listing

<u>N</u>	<u>MAG(N)</u>	<u>ANG(N)</u>	<u>MAG(N+1)</u>	<u>ANG(N+1)</u>
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

Entire listing

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where: RE(N) = Real amplitude of FFT
IM(N) = Imaginary amplitude of FFT
MAG(N) = Magnitude of FFT
ANG(N) = Angle between real and imaginary components
N = Spectral line

A-9. ACCEPTANCE CRITERIA

The contractor shall install the software package(s) on the existing Harry Diamond Laboratories (HDL) system (T5021) and perform all checkout and debugging operations to ensure compliance with these specifications.

Following compliance with requirements in the above paragraph, the contractor shall conduct a 40-hr training program at the HDL facility to instruct personnel in the use of the software package(s) and the system.

The requirements stated above shall be complied with within 30 calendar days starting with the installation of the software package (this period does not include the 40-hr training program).

Satisfactory compliance with the performance requirements listed in section A-10 as well as the requirements listed in section A-9 shall constitute official acceptance of the contractor software and/or hardware package(s) relative to these specifications.

A-10. PERFORMANCE DEMONSTRATION TESTS

A-10.1 TWC Testing

The performance requirements listed in section 10 shall be demonstrated with a dummy load less than or equal to 50 lb rigidly bolted to the exciter table.

During acceptance testing, the test cases listed in table A-3 shall be performed. The test cases shall be demonstrated within the existing capabilities of the (T5021) test system and in accordance with the specification requirements.

The method of programming/input of the selected transient waveforms shall be determined by HDL at the time of test and shall be in accordance with the specification requirements.

TABLE A-3. ACCEPTANCE TESTS--TWC METHOD

Pulse type	Amplitude (g)	Time (ms)	Bandwidth	No. lines
Half-sine	100	6	3000	128
Half-sine	15	20	2000	256
Half-sine	50	0.25	5000	64
Square	50	3	4000	64
Square	10	10	2000	256
Terminal peak	75	6	3000	128
Terminal peak	30	11	2000	128
Exponential decay	100	3	4000	64
Exponential decay	10	50	2000	512
Complex (Case I)	29.4	25	4000	512
Complex (Case II)	7.7	20	5000	512

In addition to the dummy load requirements, five complex transient-waveform cases shall be tested for using external (magnetic tapes) as the method of input. HDL shall supply the test data. The test data and transient waveforms selected shall be in accordance with the specification requirements.

The form of output of the generated waveform along with all applicable test data shall be in accordance with the specification requirements. HDL shall select the specific form of the output data at the time of test.

HDL shall have the right to increase the number of tests specified in table A-3 for a corresponding decrease in the number of tests specified for the transient waveform cases.

A-11. DOCUMENTATION

A-11.1 Software Packages

The software package(s) shall be furnished with two sets of operational manuals which will describe the overall operation and maintenance of the system. Included in each manual shall be a dictionary of diagnostic messages to specifically guide the operators in overcoming any operational, abort, or malfunction condition related to the software package(s) and the applicable testing. Also included shall

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be two copies of the listing of the source and monitoring programs to allow maintenance and accessibility to the control process, debugging, operations, and diagnostics.

A-11.2 Documentation Revisions

The contractor shall advise HDL of any revisions of the documentation specified in section A-11.1 for a period of 24 months following the acceptance of software package(s). Notice of the specific nature of the revisions (indicating all changes, additions, etc.) shall be made in writing to HDL within 60 days. At the end of the 24-month period, two copies of the latest documentation (as defined in A-11.1) shall be delivered to HDL at no additional cost.

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